The ProtoDUNE Detectors at CERN

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for the DUNE Collaboration

Joint Experimental-Theoretical Physics Seminar
Fermilab
August 18, 2017

Outline

- Introduction
- ProtoDUNE goals

- CERN infrastructure
- Cryostats
- Detector layout
  - Single phase LAr
  - Dual phase LAr

Common sub-systems

- Measurement program
- Charged particle beams

- Timeline
- Summary

Neutrino Oscillations

Neutrinos change flavor while propagating in vacuum/matter

➔ Neutrinos have mass = evidence for physics beyond the Standard Model

Flavor

$$s_{ij} = \sin\theta_{ij}\ ;\quad c_{ij} = \cos\theta_{ij}$$

Mass

$$\boxed{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}$$

atmospheric & accelerator

$\theta_{23} = (45 \pm 3)^o$
$|\Delta m^2_{32}| = (2.52 \pm 0.04)\times 10^{-3}\ eV^2$

reactor & accelerator

$\theta_{13} = (8.5 \pm 0.15)^o$
$|\Delta m^2_{31}| = (2.52 \pm 0.04)\times 10^{-3}\ eV^2$

solar & reactor

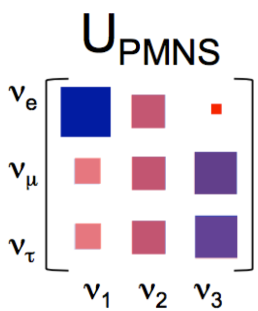
$\theta_{12} = (33.6 \pm 0.8)^o$
$\Delta m^2_{21} = (7.50 \pm 0.18)\times 10^{-5}\ eV^2$

CP violation phase: $\delta_{CP} \approx -90^o$?

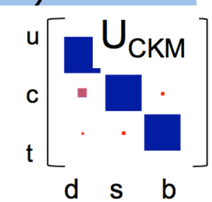
PMNS (Pontecorvo, Maki, Nakagawa, Sakata) – matrix describes mixing between flavor and mass eigenstates

Key open questions in neutrino physics

- Is there CP violation in the lepton sector ?
- Which mass hierarchy is correct ?
- What are the precise values of the neutrino mixing parameters ?



Mixing	Neutrinos	Quarks
θ_{12}	$(33.6 \pm 0.8)^o$	$(13.04 \pm 0.05)^o$
θ_{23}	$(45 \pm 3)^o$	$(2.38 \pm 0.06)^o$
θ_{13}	$(8.5 \pm 0.15)^o$	$(0.201 \pm 0.011)^o$
δ_{CP}	$(-90\ ?\ )^o$	$(67 \pm 5)^o$



→ Test 3 flavor paradigm
→ Measure symmetry between 2nd and 3rd generation
→ Search for new/unexpected physics

DUNE

- What is the absolute neutrino mass scale ?
- Are neutrinos Dirac or Majorana particles ?
- …

DUNE Primary Physics Program

1) Long-baseline Neutrino Oscillation Physics

E $\sim$ O(few GeV)

- Measure the value of the CP phase δ
- Identify the neutrino mass hierarchy
- Perform precision neutrino physics:

  Test the 3 flavor paradigm

  Measure symmetry between 2nd and 3rd generation

  Measure neutrino cross sections

High precision measurements to look for the unexpected

Energy range

2) Nucleon Decay

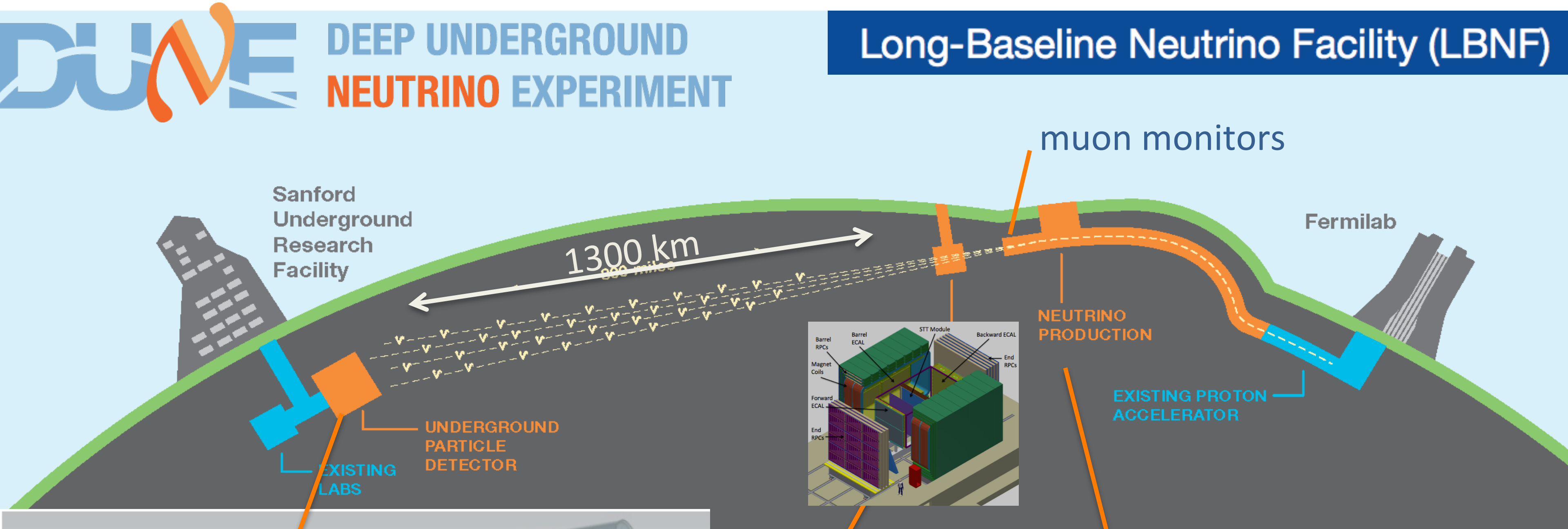
Target SUSY-favored mode: $p \rightarrow K^{+}\nu$

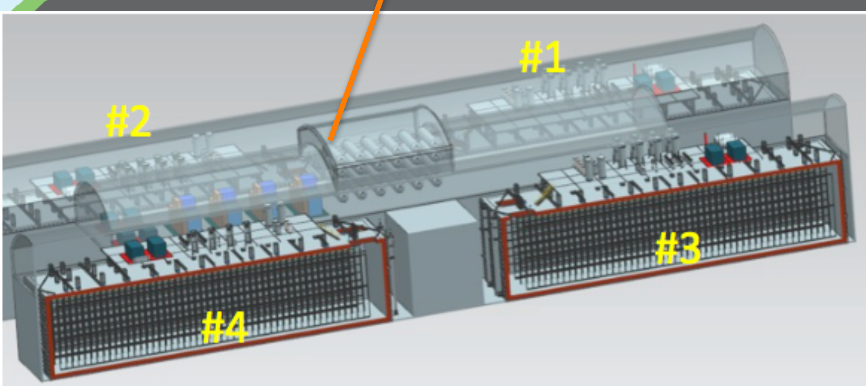
3) Supernova burst and astro-physics

E $\sim$ O(10 MeV)

Galactic core collapse supernova, best sensitivity to ν_e

DUNE and LBNF Overview





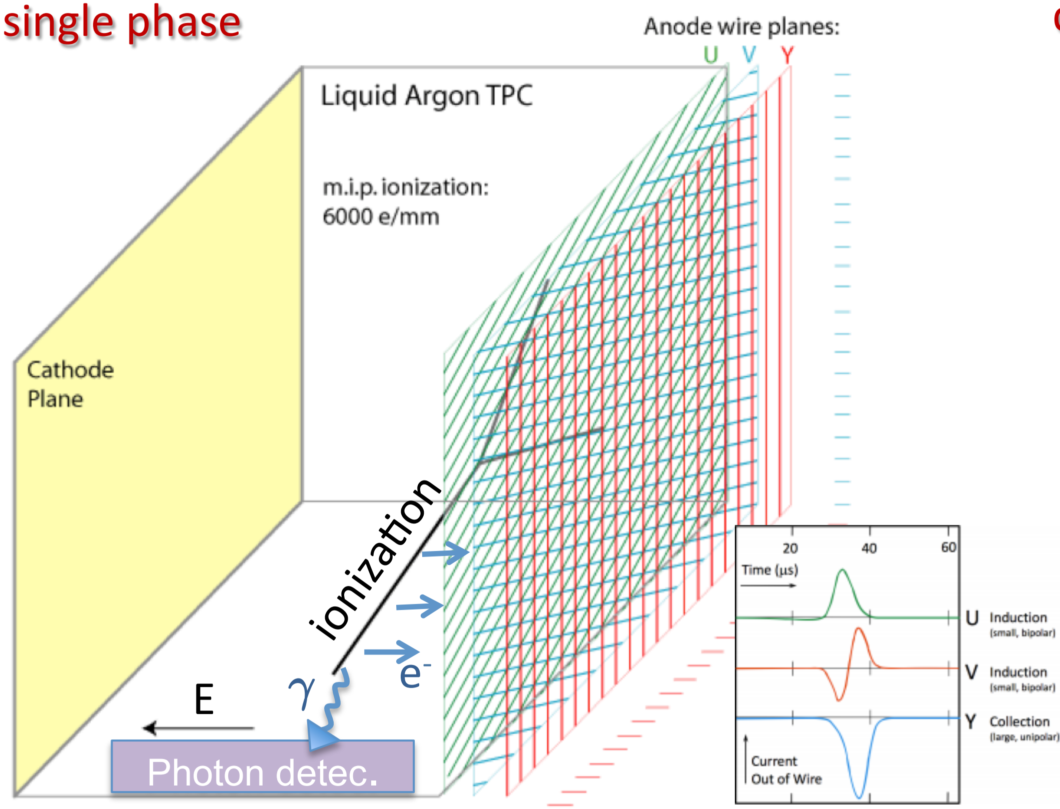
High precision
near detector
at 574m

Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

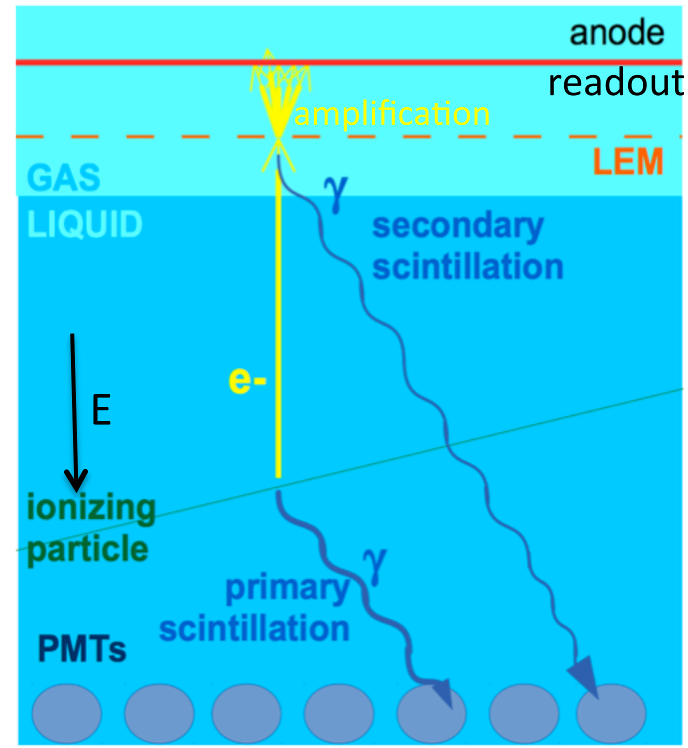
- Four identical caverns/cryostats deep underground
- Staged approach to four independent 10 kt LAr detector modules
- Single-phase and dual-phase readout under consideration

LAr TPC Technologies

single phase



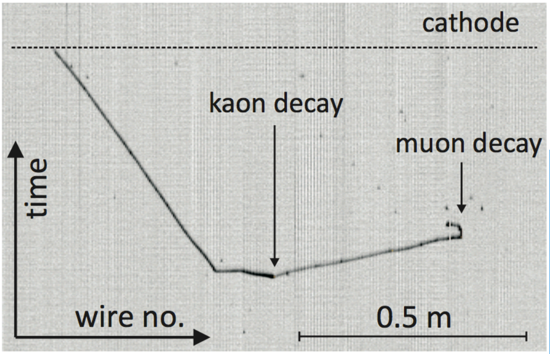
dual phase



- Ionization: $\sim$ 60,000 e⁻/cm for mip (for E $\approx$ 500V/cm)
  → Provides detailed imaging, calorimetric and particle identification (PID)
- Scintillation (128nm): $\sim$24,000 γ/MeV (for E $\approx$ 500V/cm)
  → offers event trigger (t_0) information + improved calorimetric information

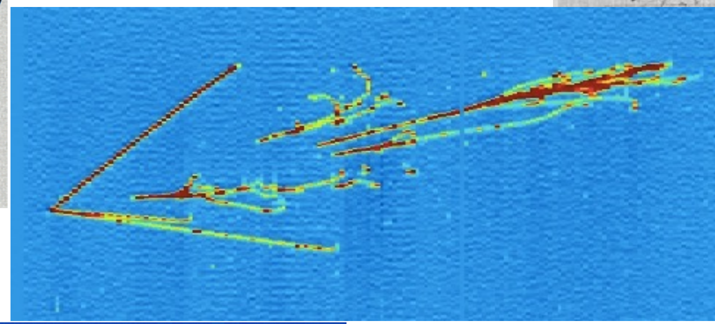
Sample event displays

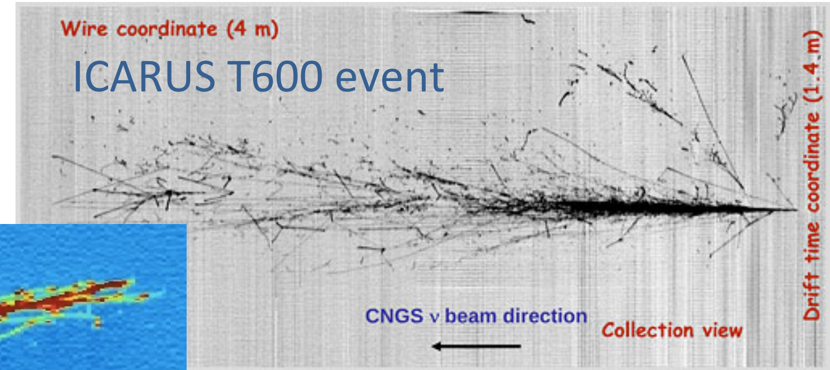
ICARUS T600 event

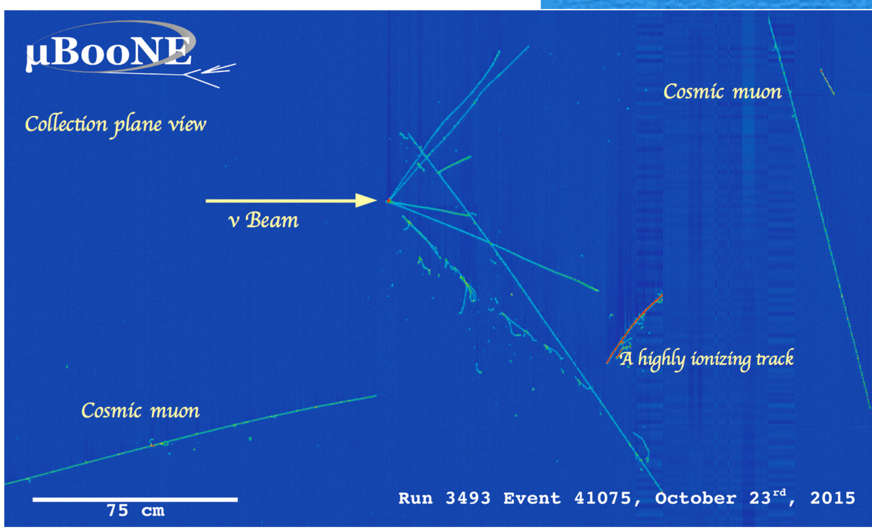


Antonello et al.,
Adv. HE Phys. (2013) 260820

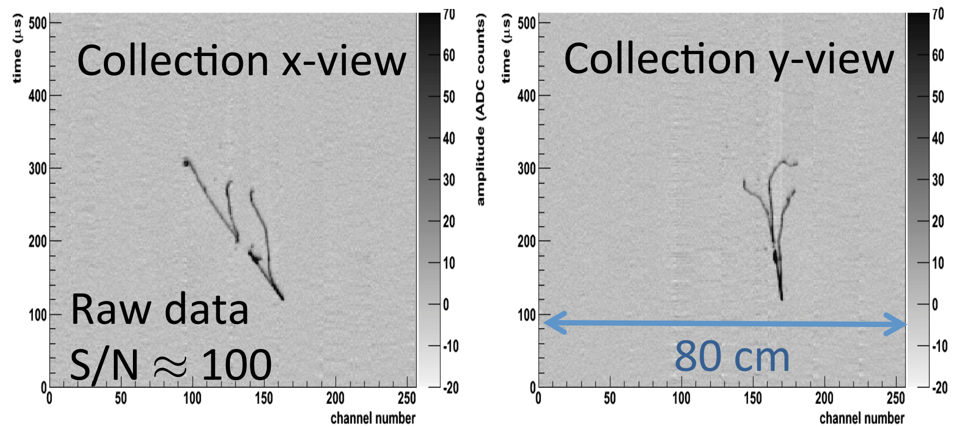
ArgoNeuT event







Dual phase 250l prototype detector



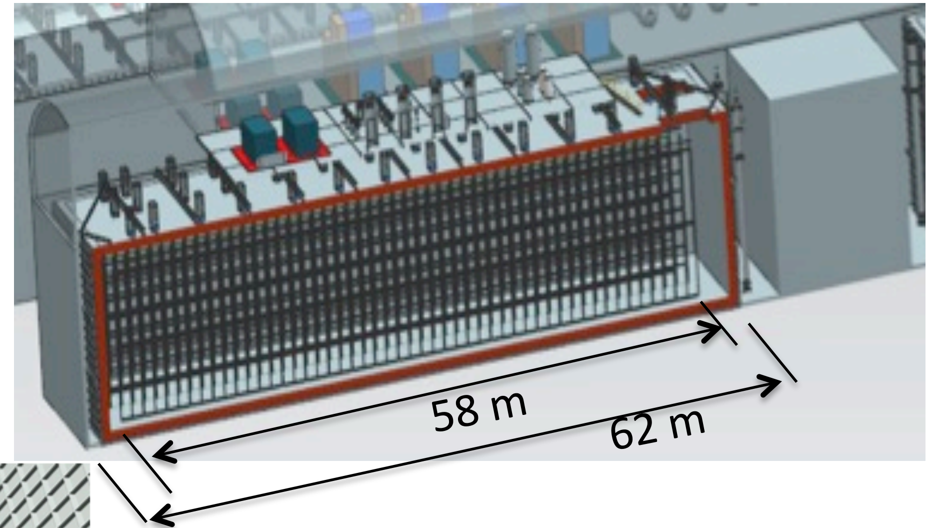
→ **Excellent precision and 3D track/shower information for single and dual phase LAr TPCs**

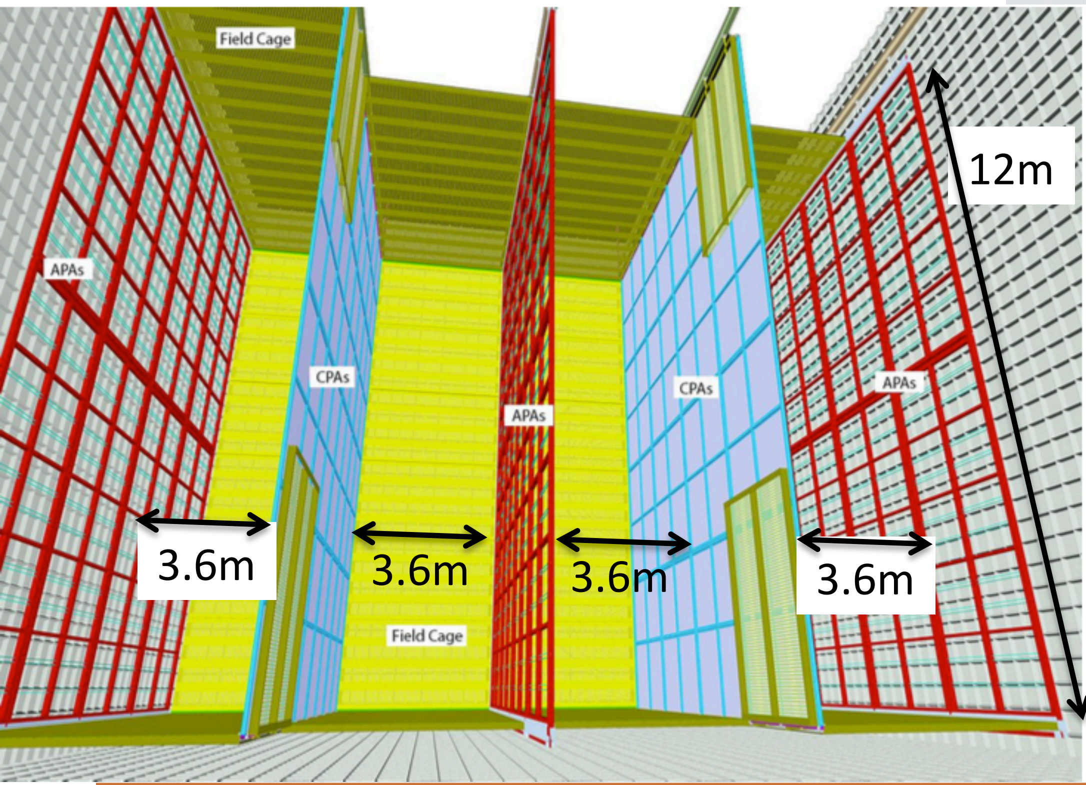
→ **Liquid argon offers large target mass and is scalable**

Single-Phase LAr Detector

Readout of
- Ionization charge and
- scintillation light

Detector mass [kt]	
total	17.1
active	13.8
fiducial	11.6





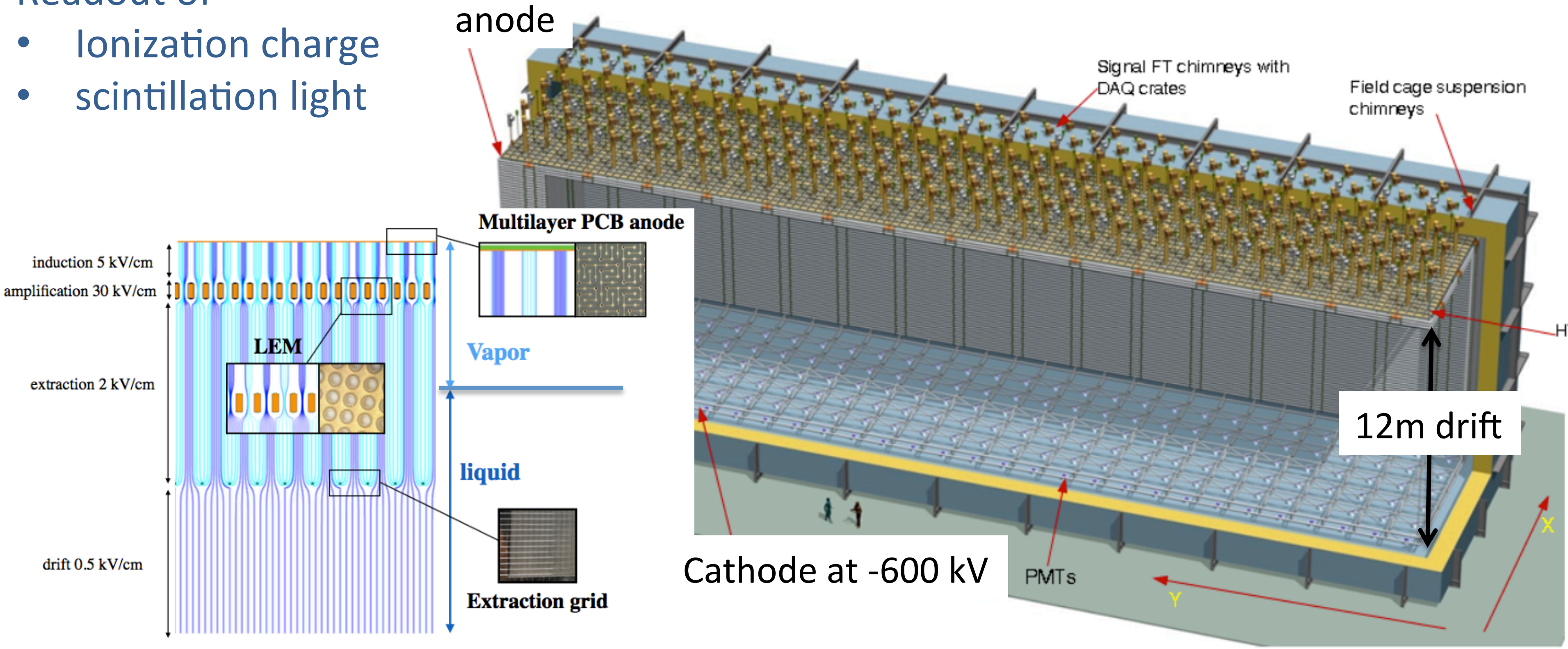
Time Projection Chamber:
wire Anode Planes (APAs)
induction + collection wires
2 cathode planes at -180 kV

4 drift regions: 3.6m drift each

Photon Detection System
integrated in APAs to measure
non-beam event timing

Dual-Phase LAr Detector

Readout of
- Ionization charge
- scintillation light



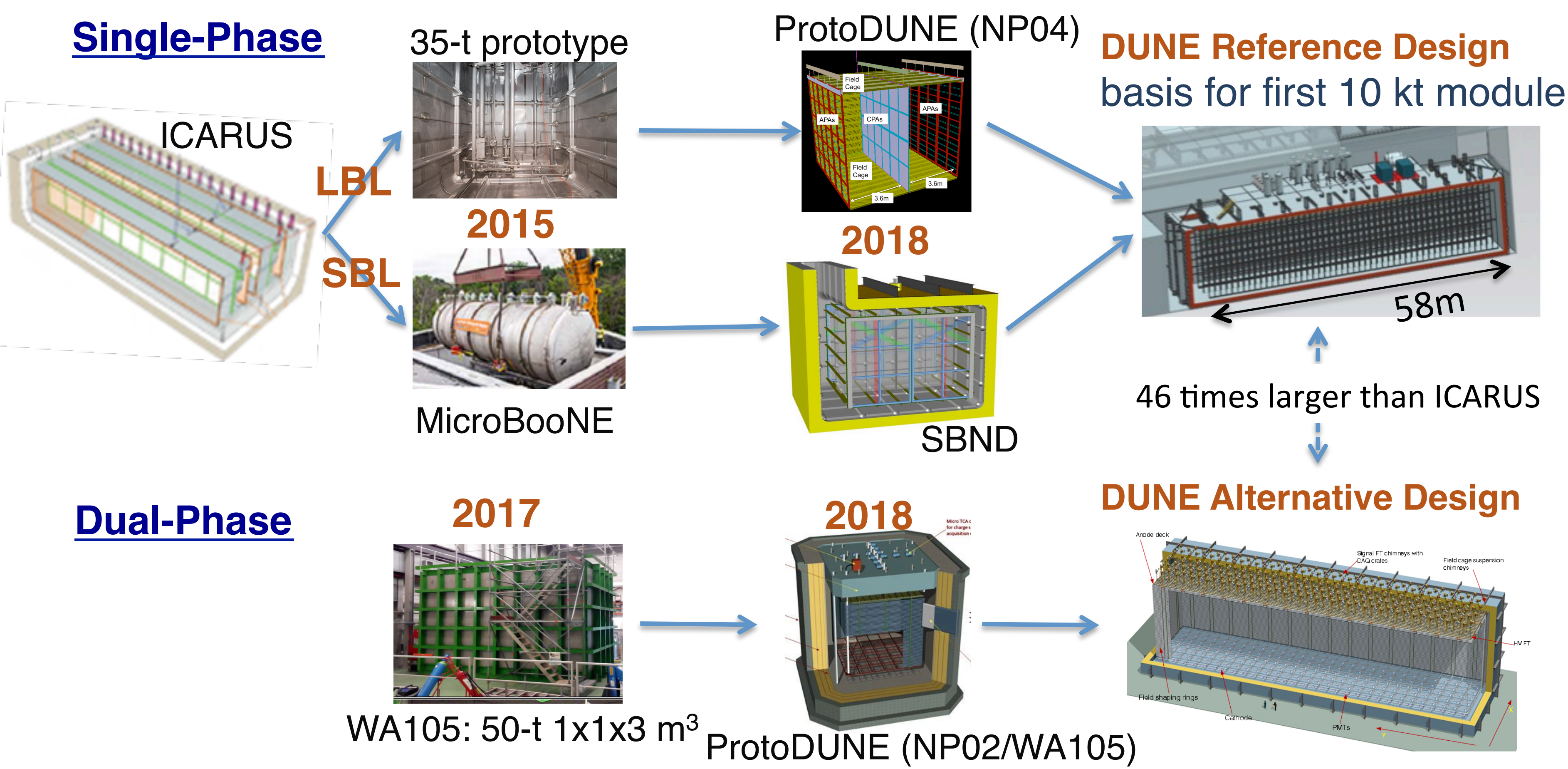
Ionization charge extracted into Ar gas phase
charge amplification via large electron multipliers (LEM) before readout

[strengths: 2 dimensional charge collection, robust S/N with tunable gain,
insensitive to microphonic noise, different systematics]

→ If demonstrated at large scales, could be used as alternative design for 2nd or subsequent 10 kt far detector modules

LArTPC Development Path

Fermilab SBN and CERN neutrino platform provide a strong **LArTPC** development and prototyping program



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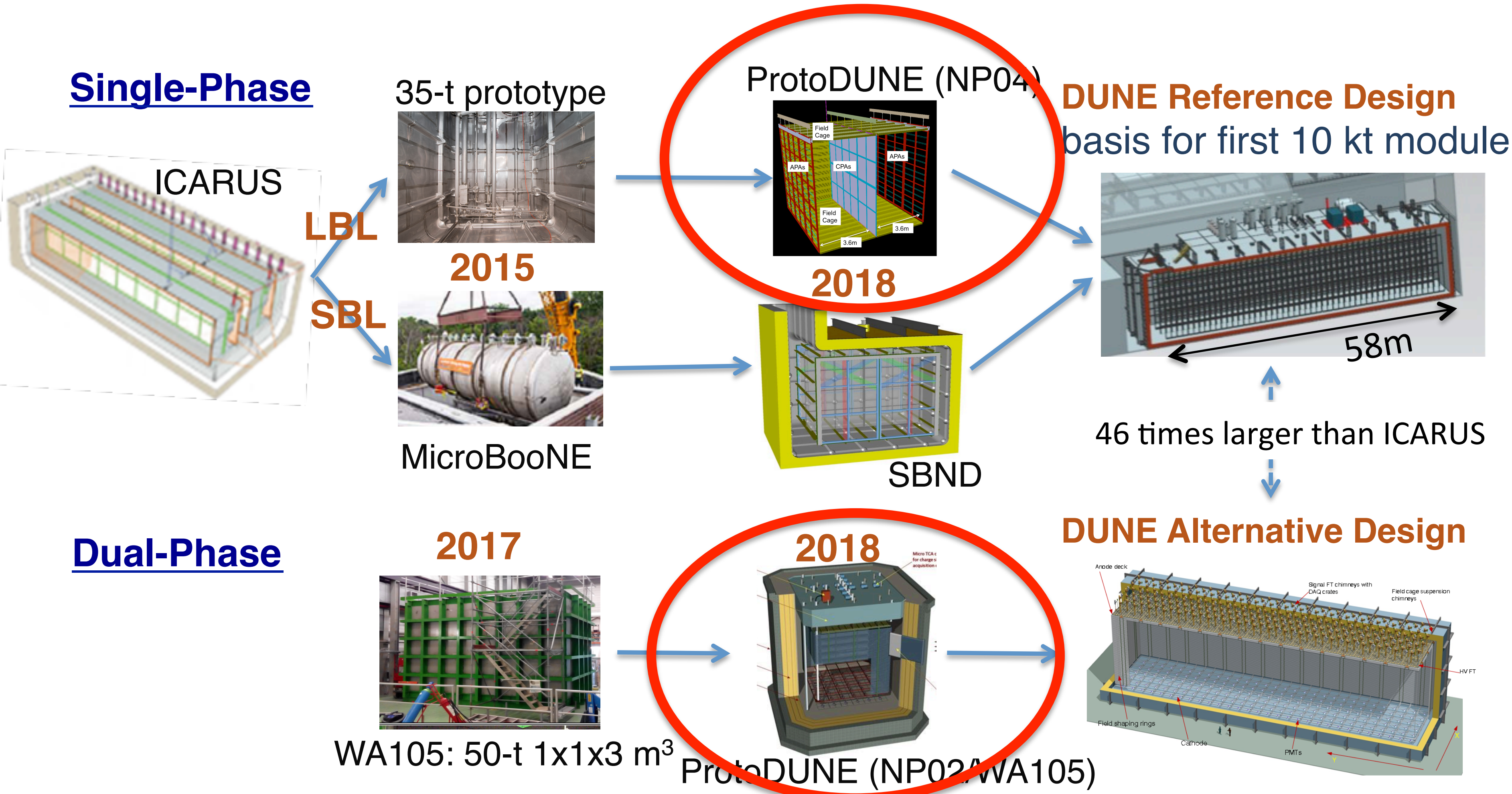

ProtoDUNE High Level Goals

Detector Production:

- Establish production process and quality assurance of full scale detector components

  →mitigate associated risks and validates cost for DUNE far detector

Installation:

- Test of interfaces between detector elements

Operation : (Cosmic ray data)

- Validate detector design and (long term) detector performance
- Achieve required LAr purity

Test beam data:

- Assess detector physics response and **systematic uncertainties**

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Operation : (Cosmic ray data)

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Test beam data:

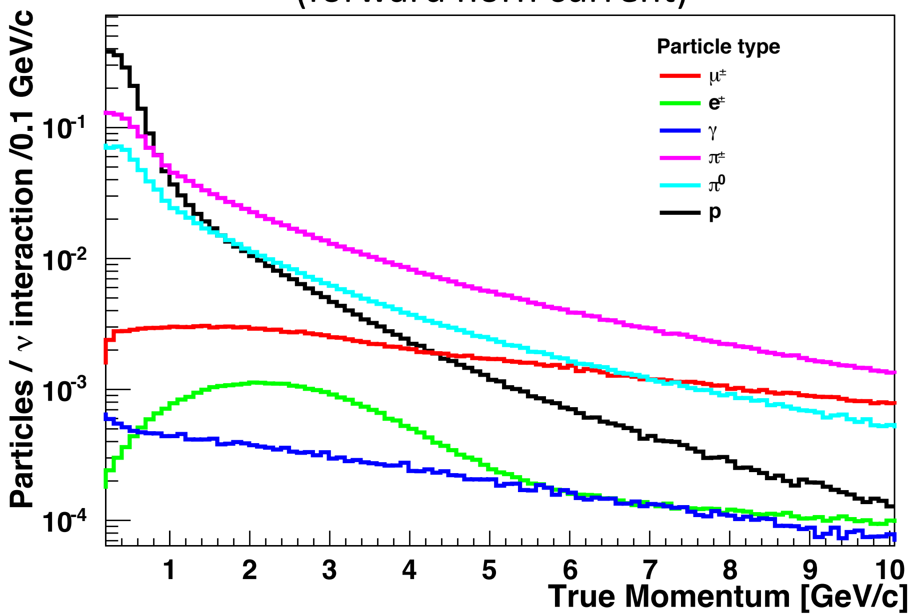
- Assess detector physics response and **systematic uncertainties**

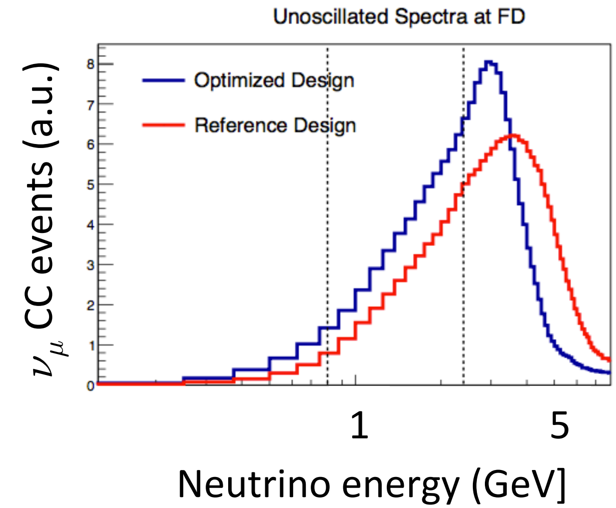
To be most relevant for DUNE requires charged particle beam to cover energy range and particle types as expected for DUNE ν interactions

ProtoDUNE Charged Particle Requirements

Expected secondary particle spectra in DUNE far detector; uses ν-beam flux as input

(forward horn current)





Uses GENIE to simulate interactions (Ar 40 cross section) and final states

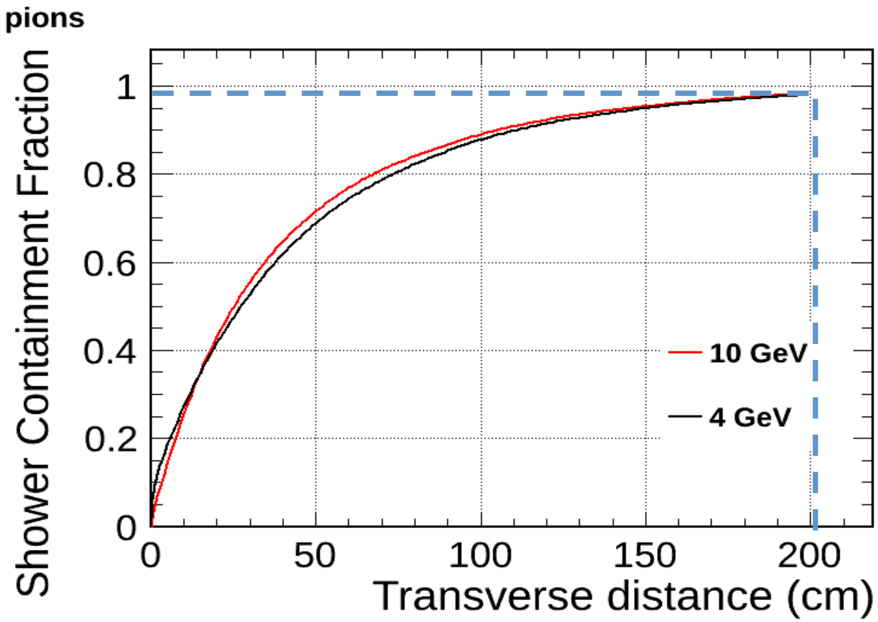
Relevant individual charged particles to be studied in CERN beam test
→ Energy ranges of : sub-GeV to several GeV
NOTE: particles embedded in showers → study topologies

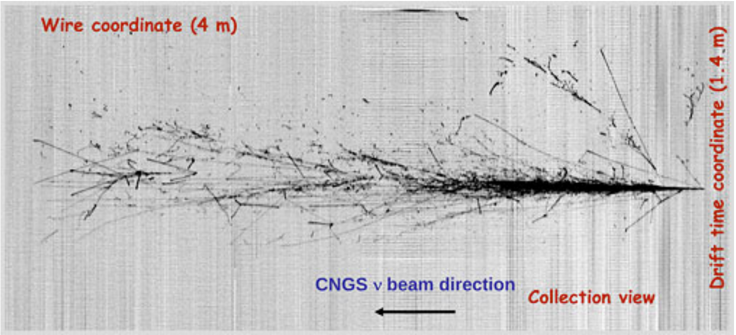
→ Affects particle containment and detector size

Detector Size/Dimensions

Engineering:
test multiple full-scale components assembled into functional sub-unit

Measurement:
energy bias studies require shower containment

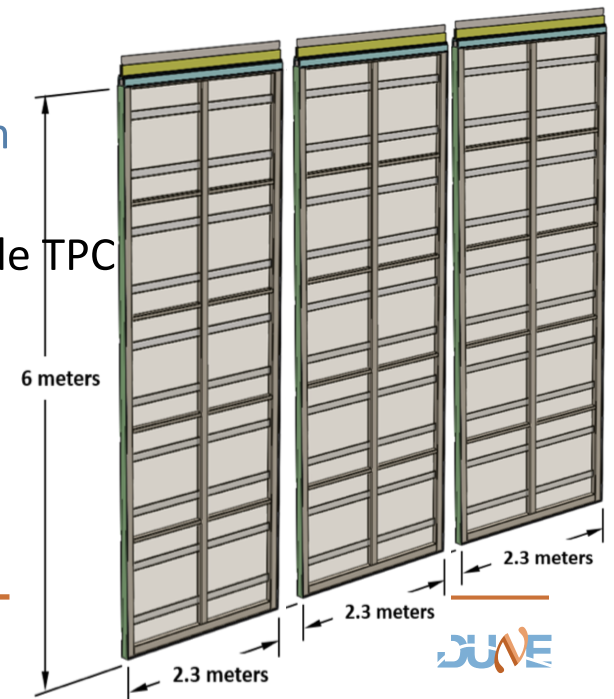




$\sim$99 % containment envelope
Transverse: 2.1 m
Longitudinal: 5.3 m

APA

3 APA wide TPC

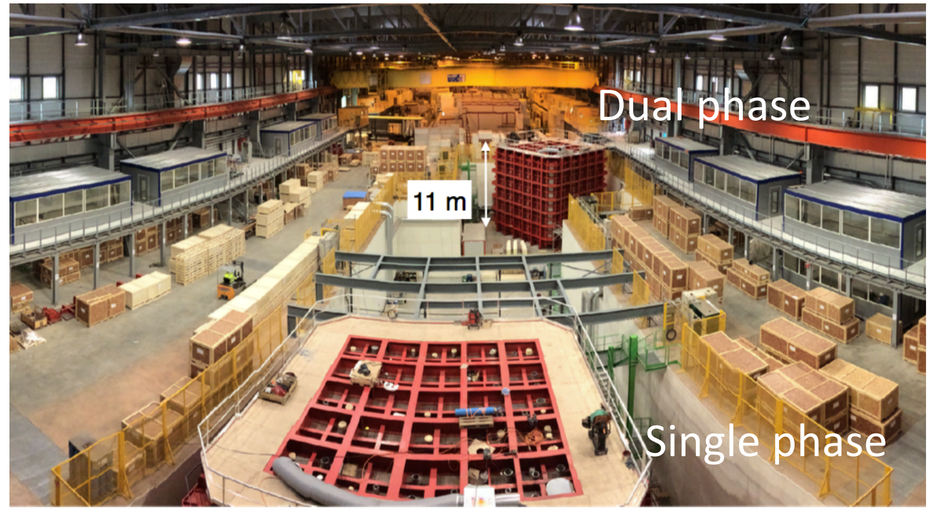


→ active volume size requirements:
6m × 5m × 5m
→ **2 drift volumes** (3.6m each))

CERN Infrastructure (EHN1)

ProtoDUNE Milestones

ProtoDUNE approved at CERN



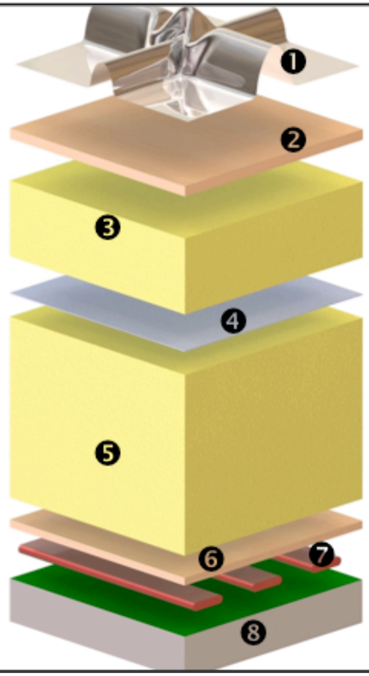
time

10/2015 04/2016 09/2016 11/2016 4/2017 fall/2017

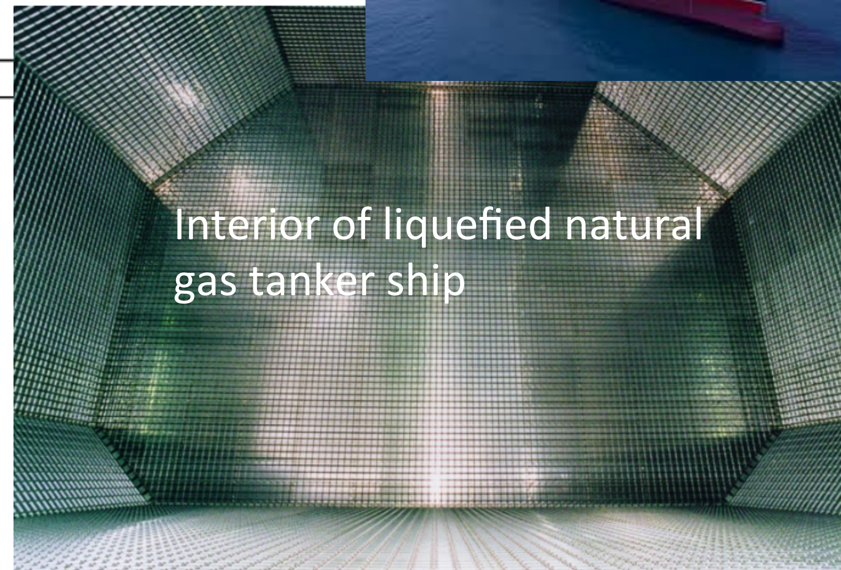
Detector installation

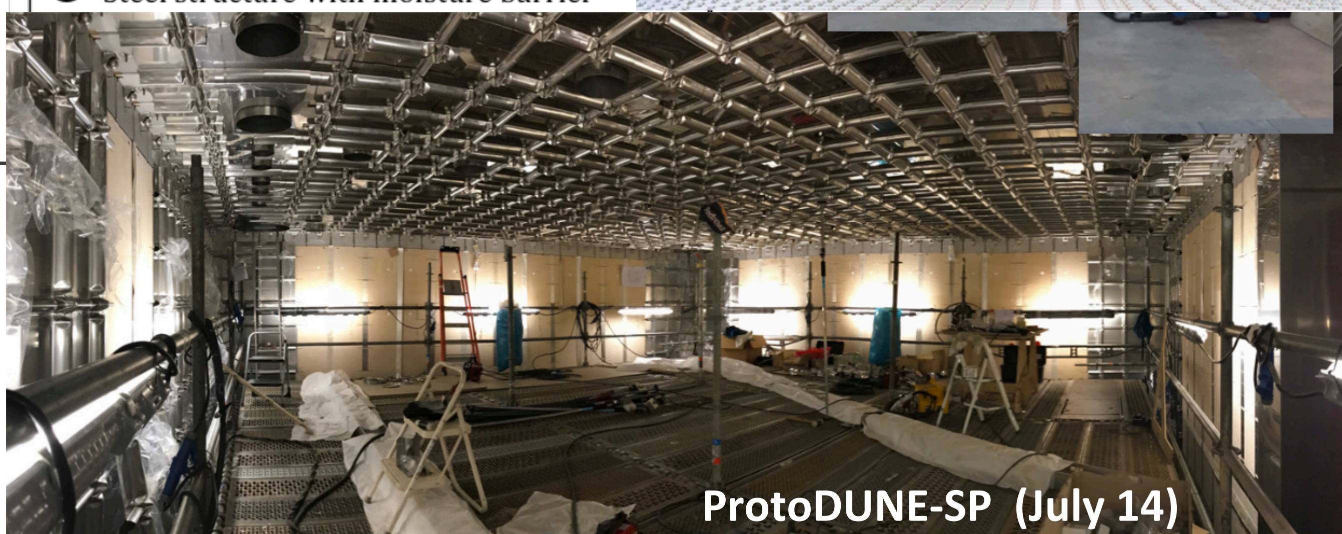
Cryostat Technology

Membrane cryostat (well established/commercial technology)
→ cryostats completed 8/2017



1. Stainless steel primary membrane
2. Plywood board
3. Reinforced polyurethane foam
4. Secondary barrier
5. Reinforced polyurethane foam
6. Plywood board
7. Bearing mastic
8. Steel structure with moisture barrier

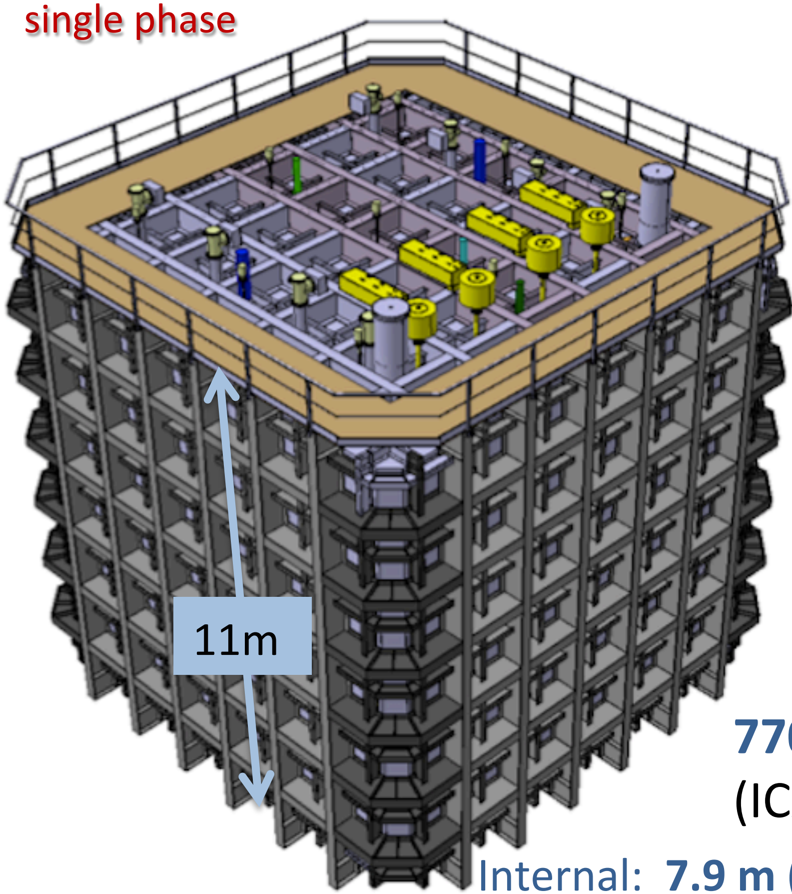




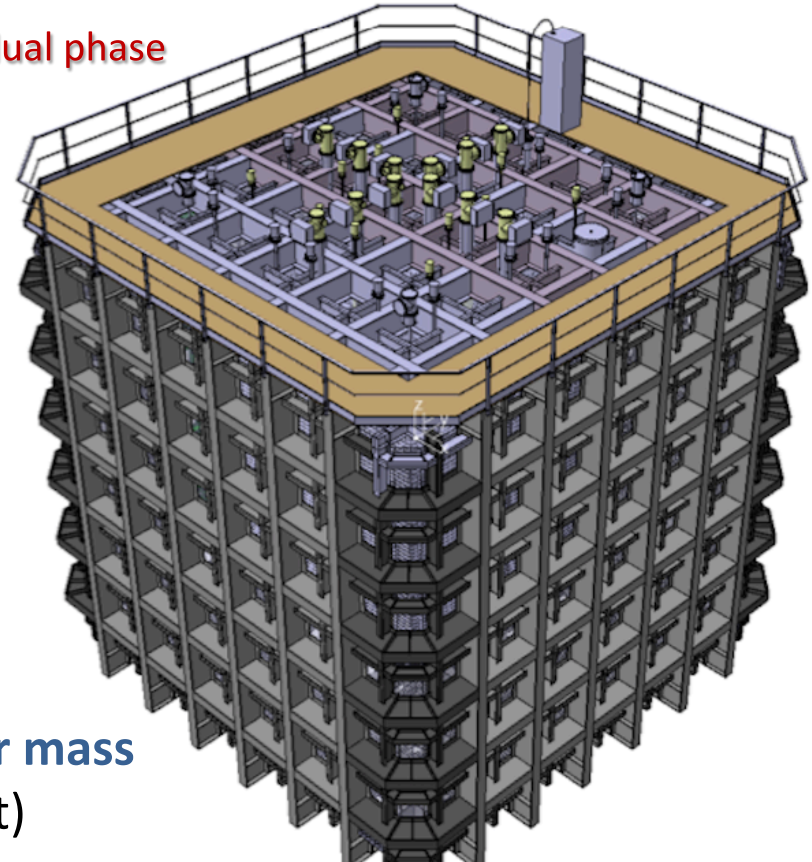
ProtoDUNE Cryostats

Use nearly identical cryostats for single and dual phase protoDUNE

single phase



dual phase

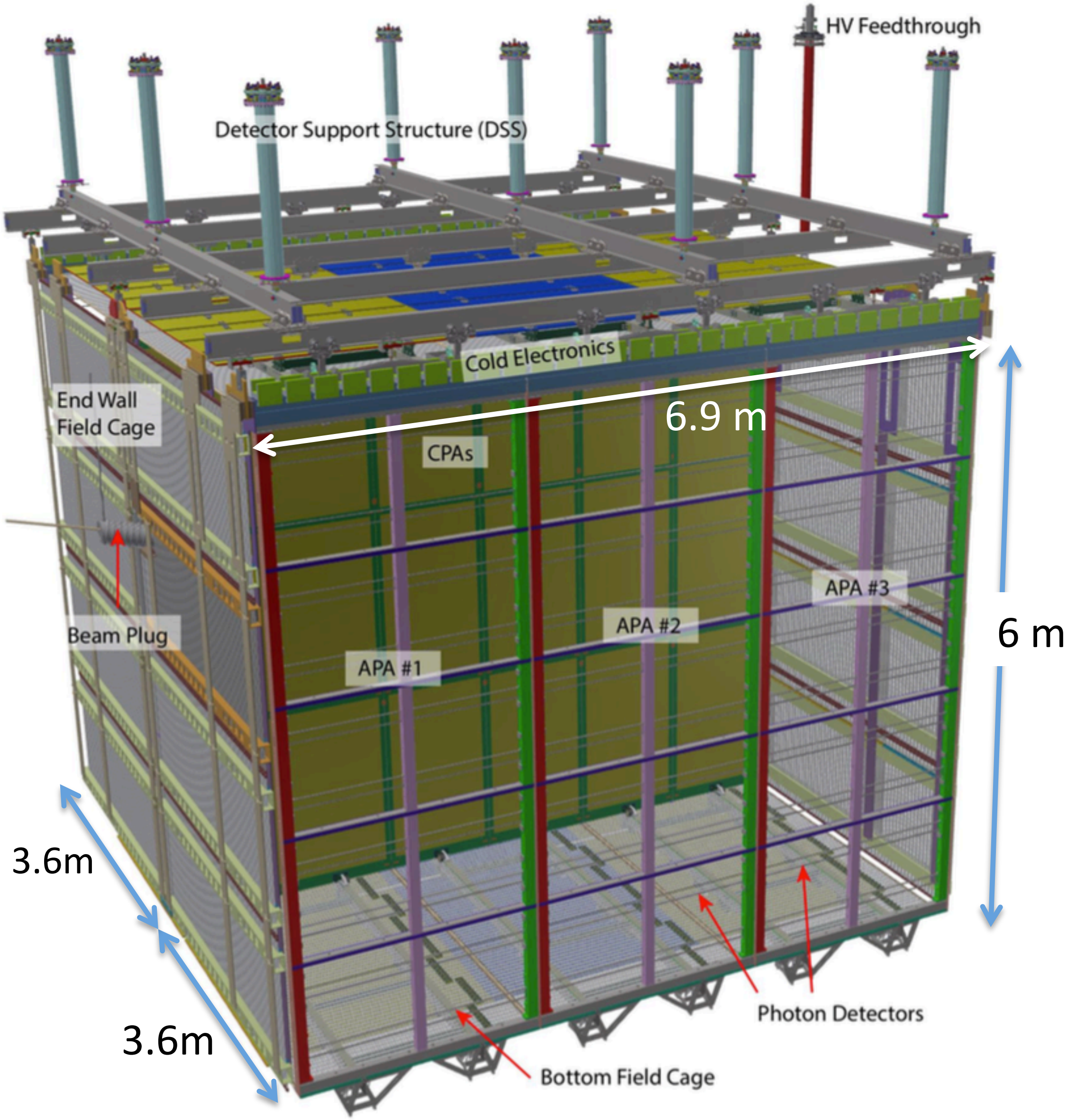


770 t total LAr mass
(ICARUS: 600 t)

Internal: **7.9 m (Transv) x 8.5 m (Parallel) x 8.1 m (Height)**
External: **10.8m (Transv) x 11.4 m (Parallel) x 11.0 m (Height).**

→ ProtoDUNE cryostats serve as prototypes for the DUNE 10 kt cryostats

Single Phase ProtoDUNE TPC



Detector components are same as for DUNE far detector

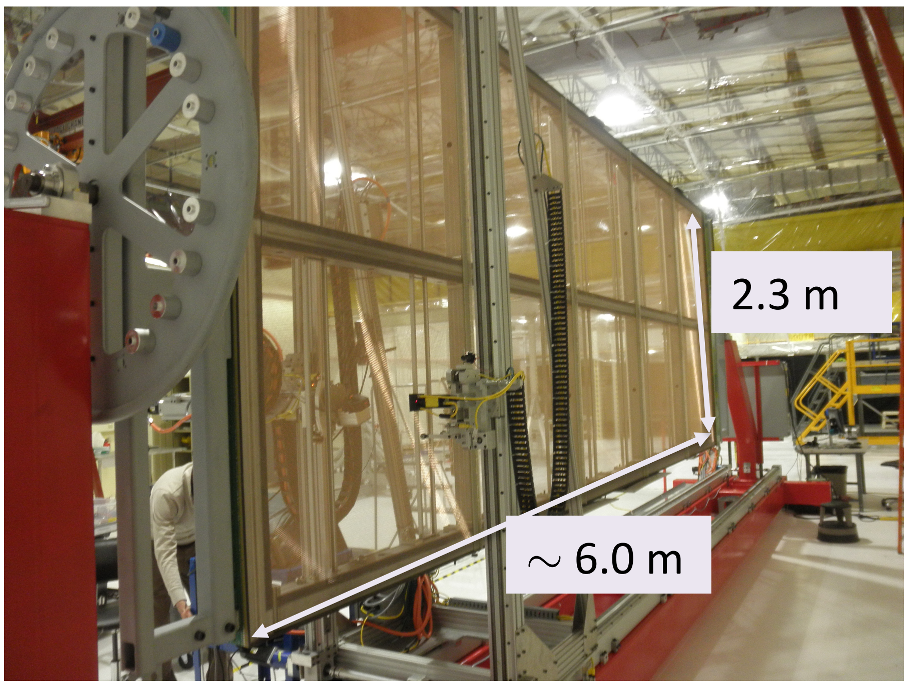
Keep option to reduce drift distance to 2.5m (reduced space charge effects)

Expected cosmics rate: $\sim$ 10 kHz
→useful for detector performance studies

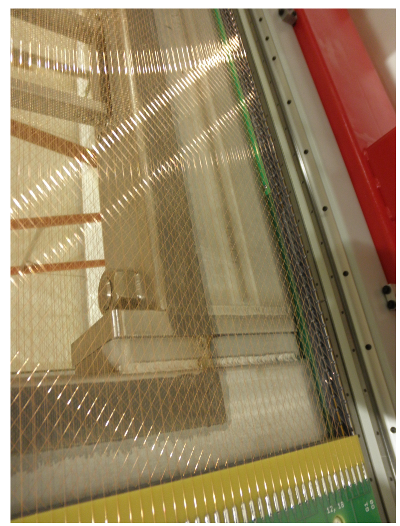
Anode Plane Assemblies (APA)

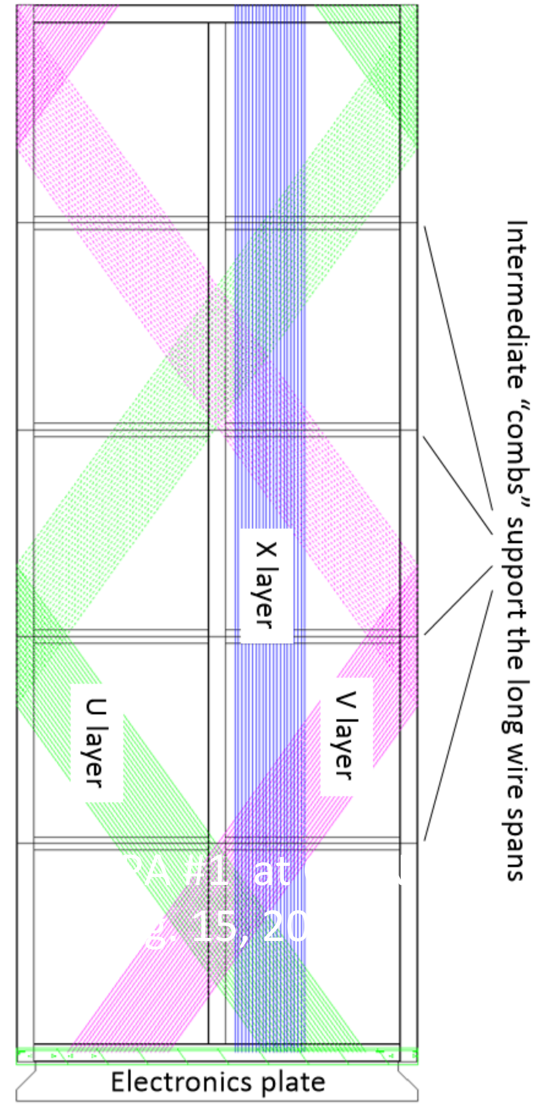
4 wire planes (4.8 mm spacing)

Function	no.	pitch [mm]	orientation	potential [V]
Collection (x)	960	4.79	vertical	820
Induction (V)	800	4.67	35.7° - wrapped	0
Induction (U)	800	4.67	35.7° - wrapped	-370
Grid	960	4.5	vertical	- 665



Wire frame detail





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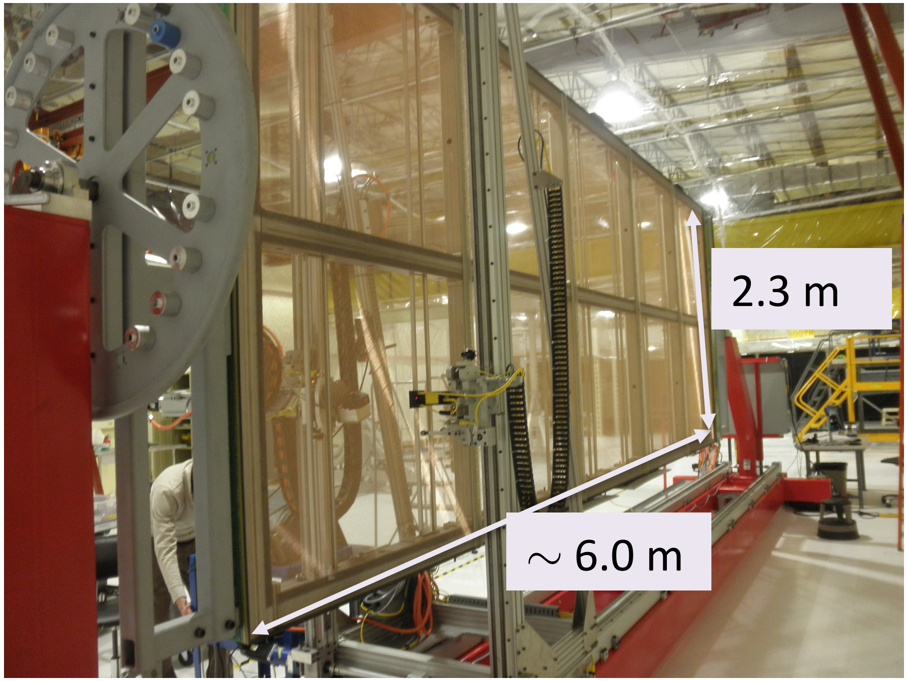

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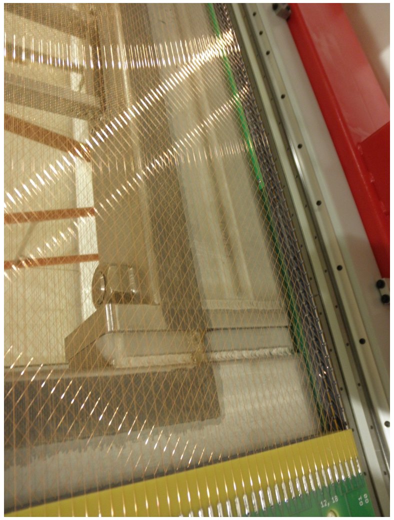
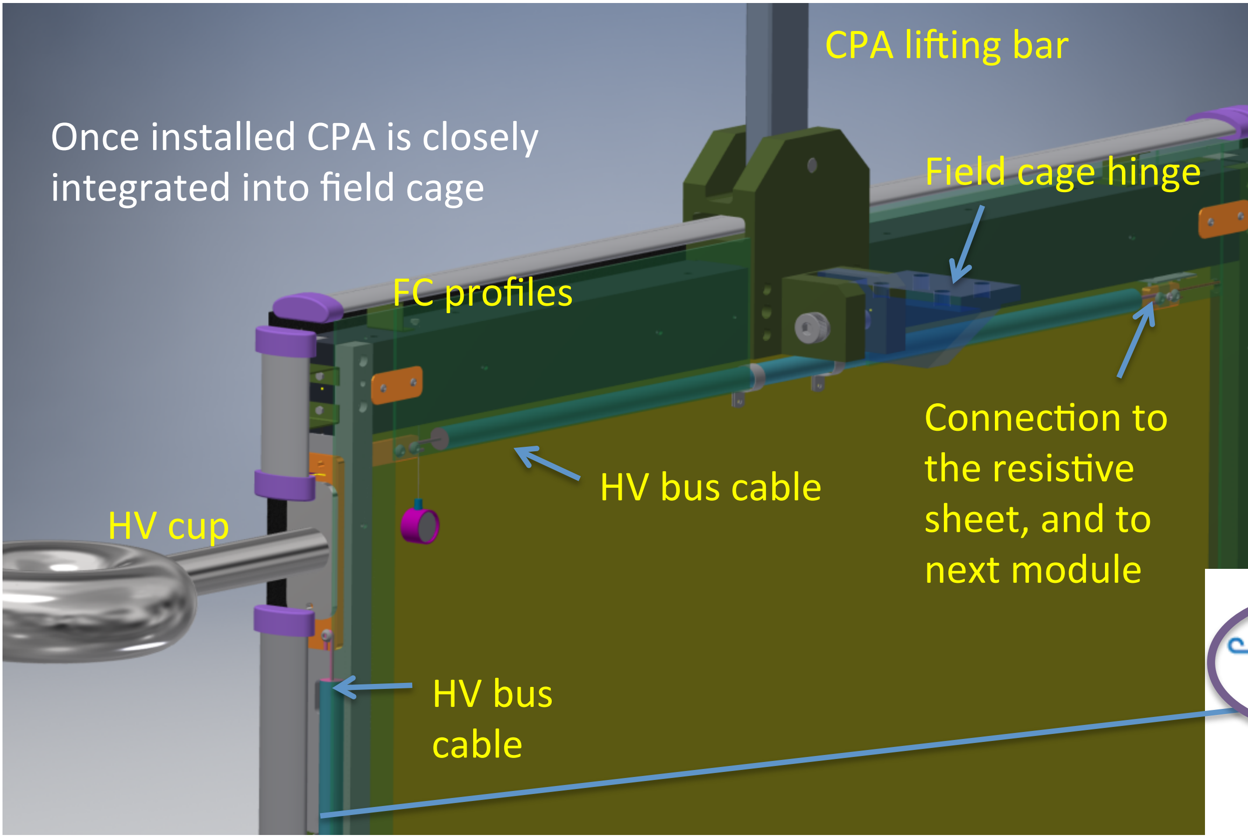
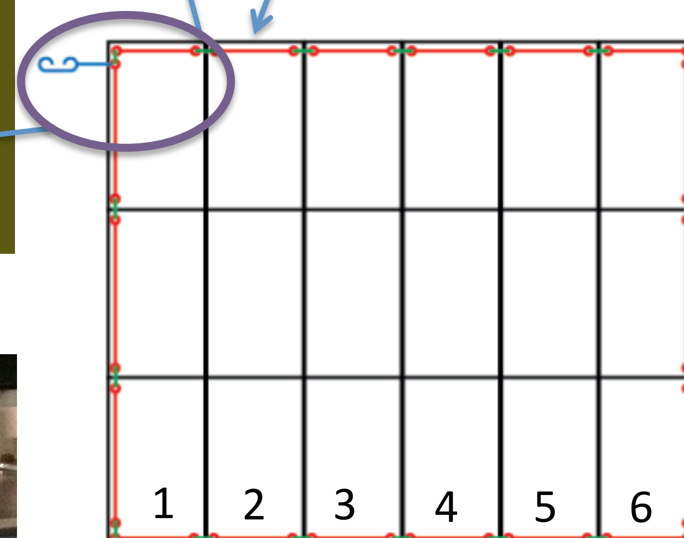


→ **DUNE far detector requires 150 APAs per 10kt module**

Cathode Plane Assembly (CPA)



HV bus provides uniform voltage

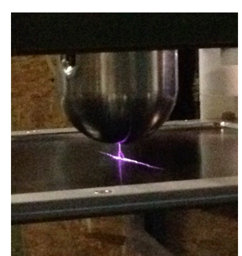


∼ 240 lbs per column

6 interconnected CPA columns (V_{bias} = - 180kV)

- Resistive material (G10 + kapton foil)

→robustness of variety of materials and coatings to sparks studied in test setup in air and LAr at CERN

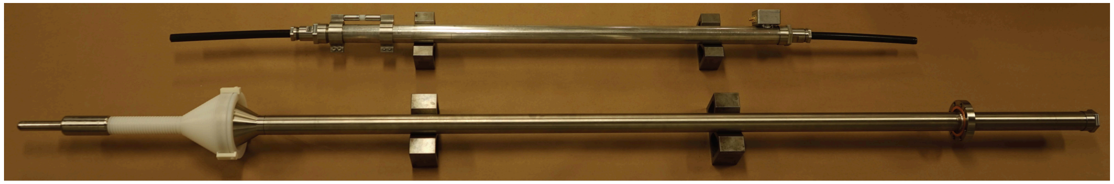


High Voltage

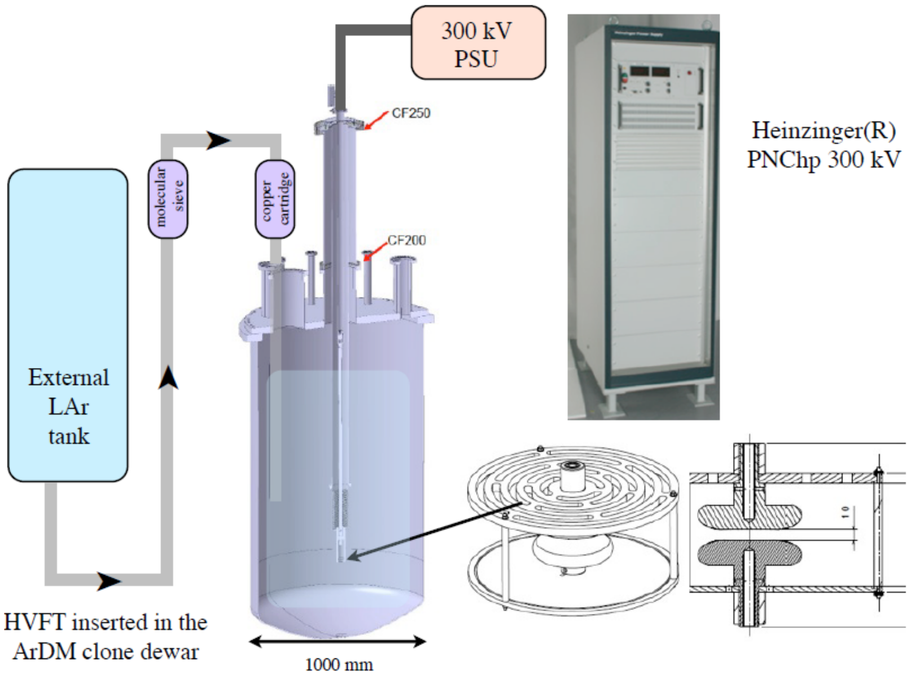
Common to both NP02 and NP04

- Required cathode HV for ProtoDUNE dual phase LAr is 300 kV

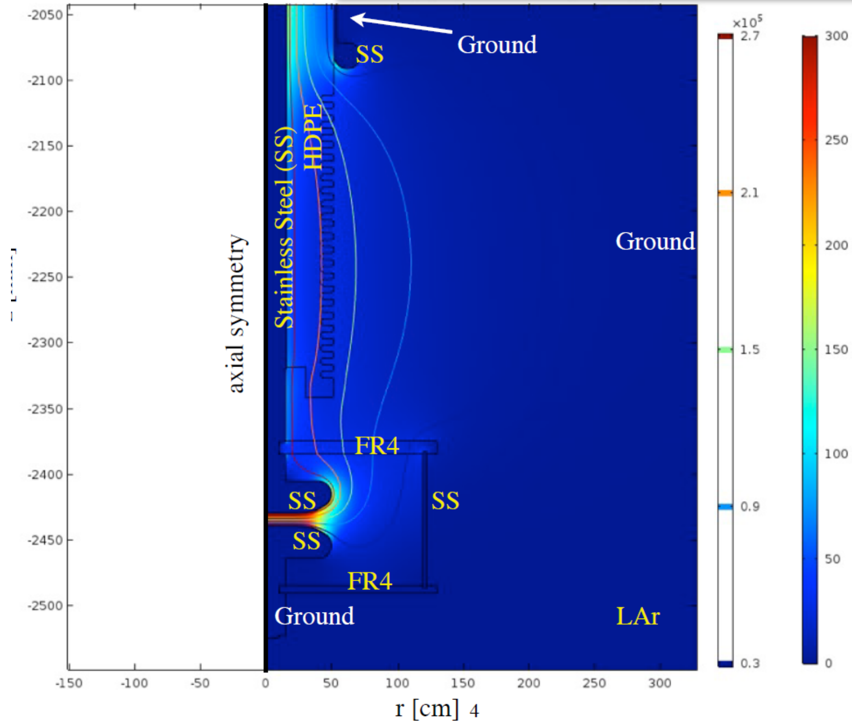
  → 0.5 kV/cm drift field (over 6m)



- FT test at CERN with 300kV Heinzinger PS



COMSOL simulation of fields around feedthrough



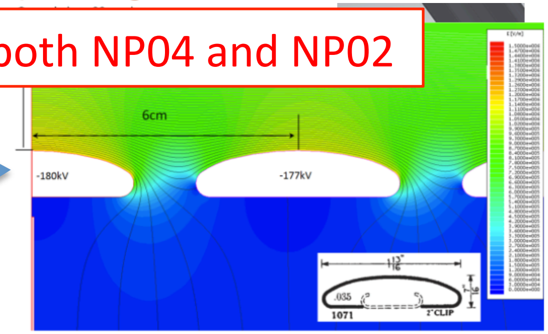
DUNE dual phase requirement: 600 kV → being developed with industry

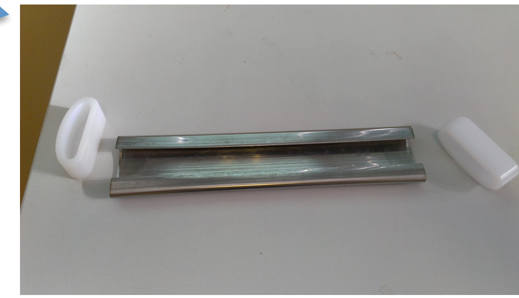
Field Cage (FC) + Resistive Divider Chain

Key elements common to both NP04 and NP02

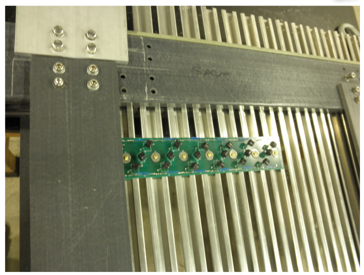
Provides uniform electric drift field

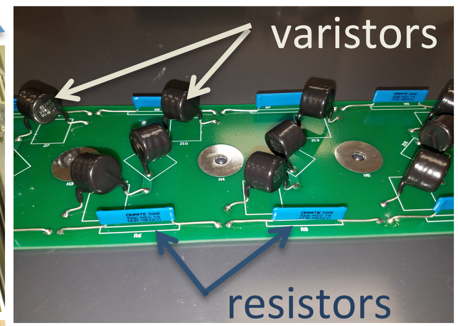
Constructed from
- roll formed Al profiles and
- Plastic caps to prevent discharges
- R-divider chain steps voltage by 3 kV between profiles

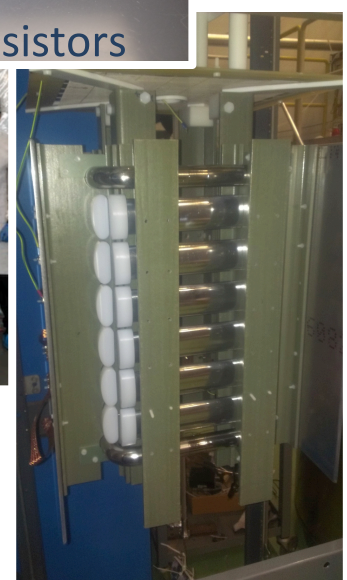




Top+ bottom:
Ground plane
FC (20 cm separation)





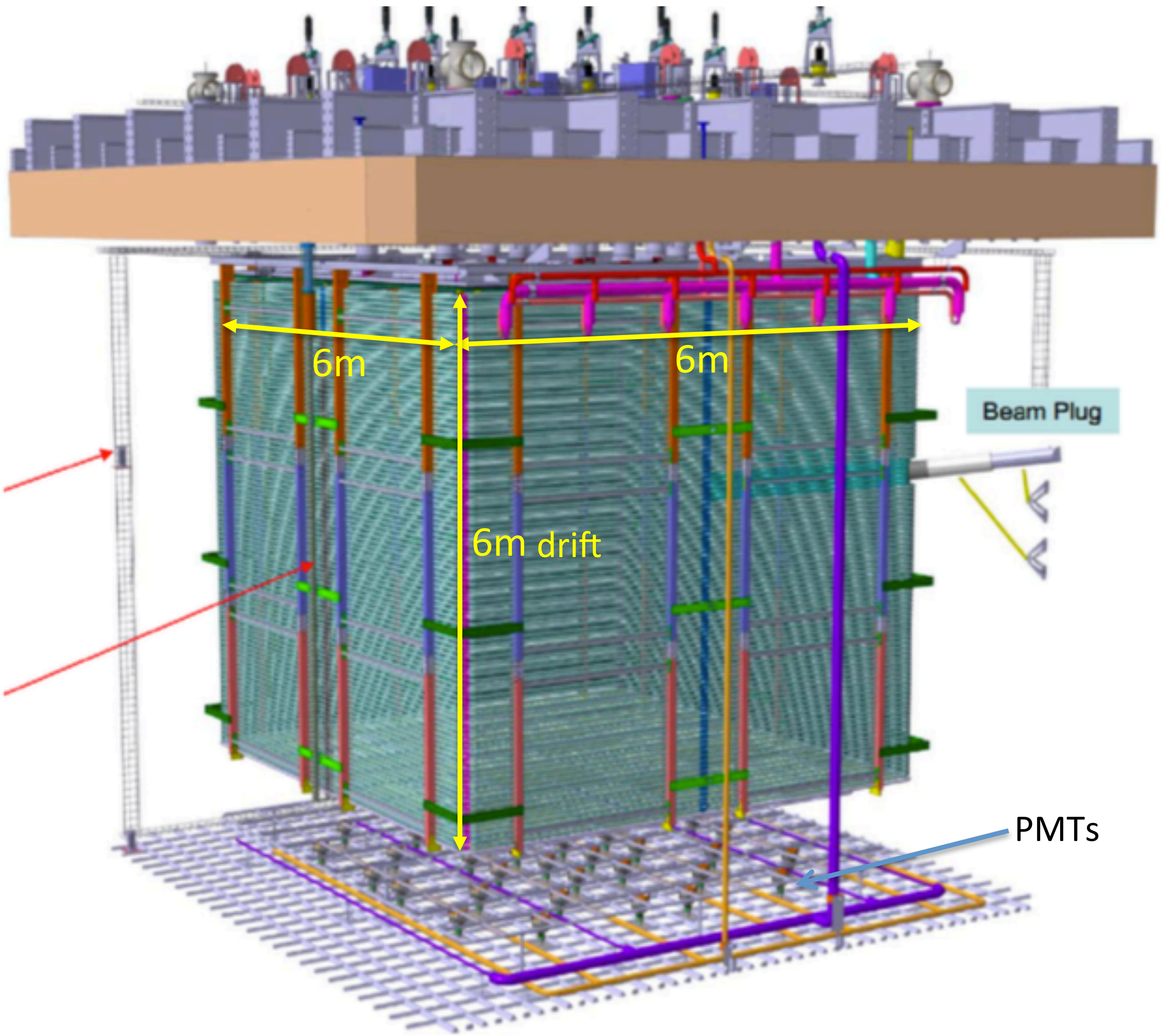


Functional test with Purified LAr:

→NO sparks observed up to 100kV

→occasional sparks above 80 kV if bubbles present

Dual Phase ProtoDUNE TPC



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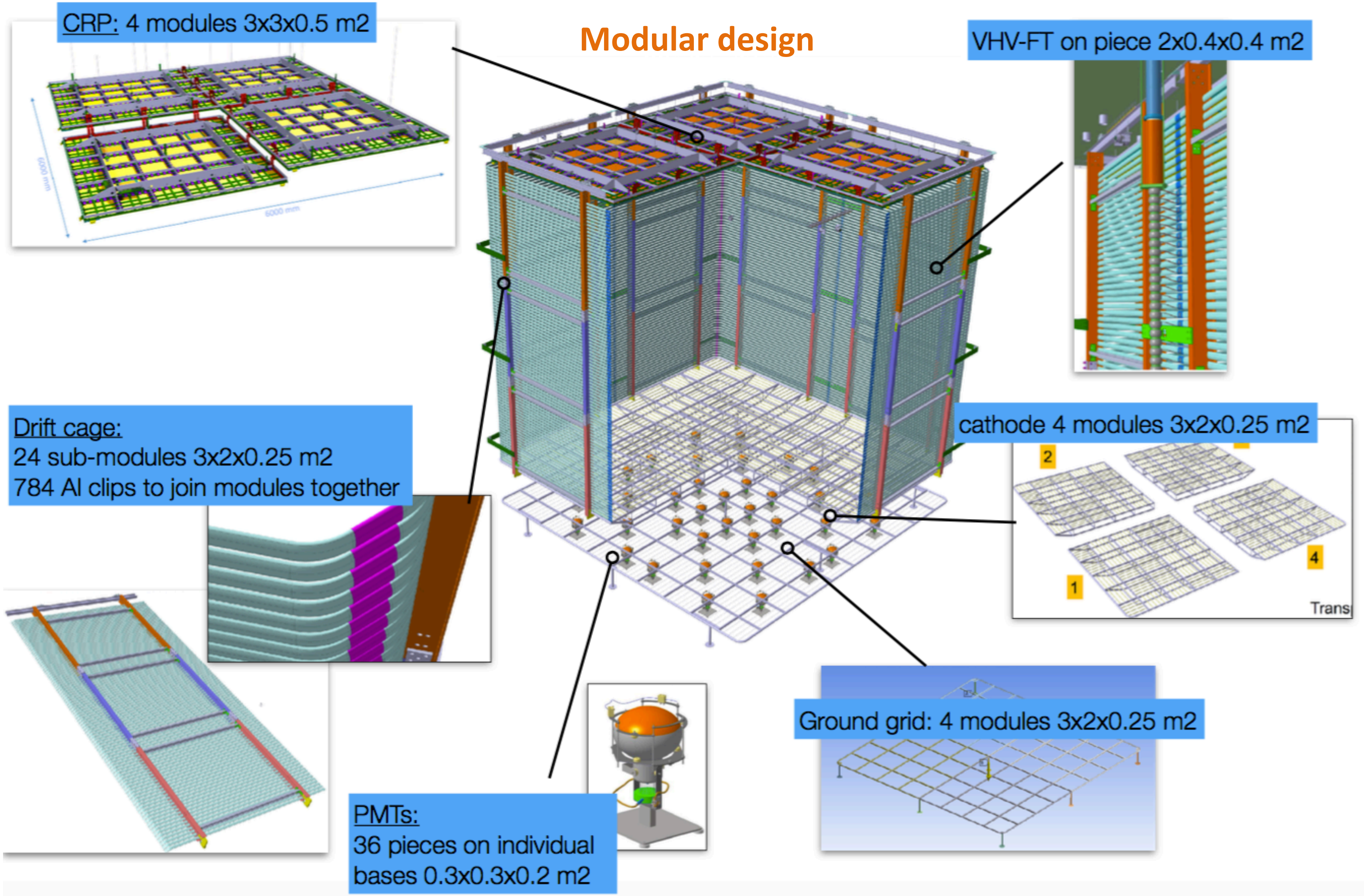
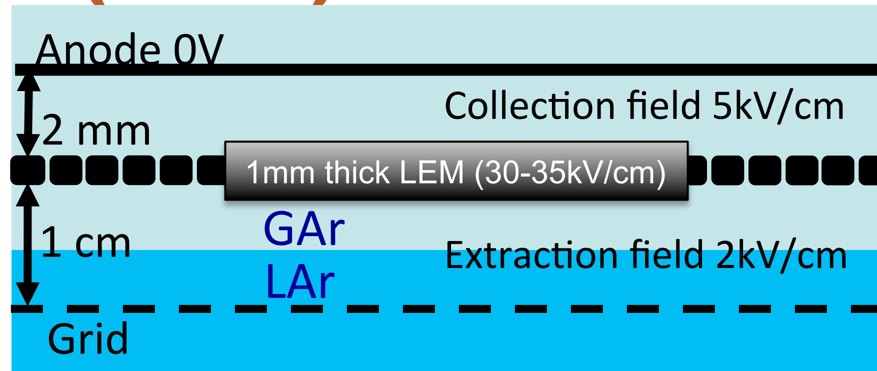
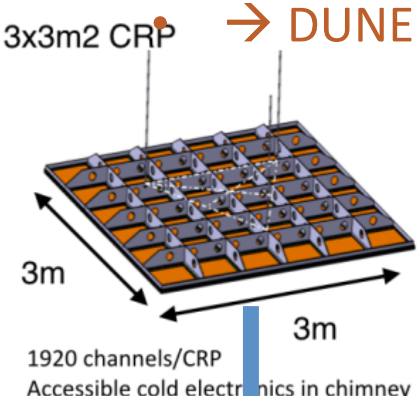


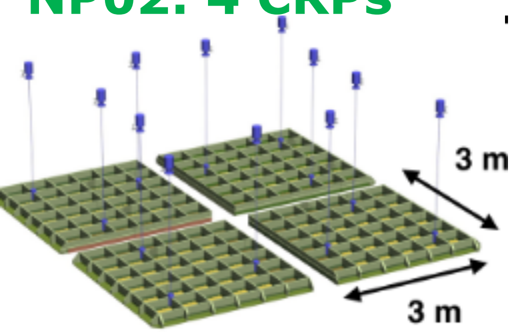
Charge Readout Plane (CRP)

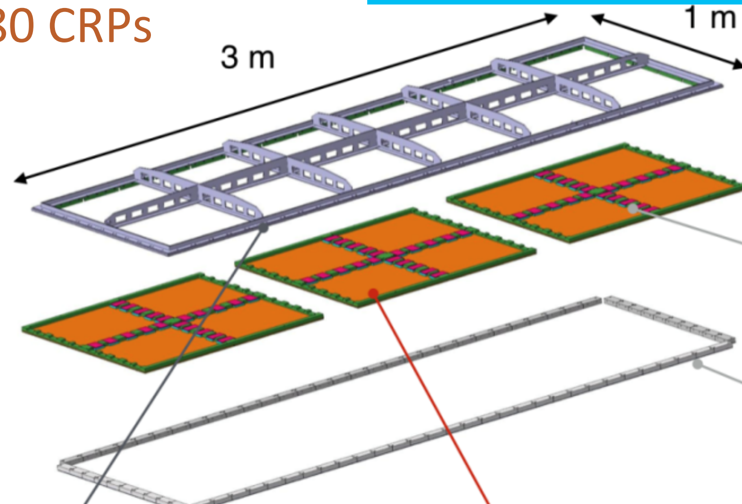
- CRP is composed of 4 3x3 m^2 readout units built from 50x50 cm^2 LEM and anodes
- Each unit has its own suspension system
- Charge is collected on 3m “strips”
- Identical structure planed for DUNE 10kt
  - → DUNE requires 80 CRPs

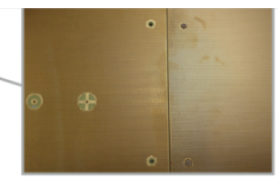


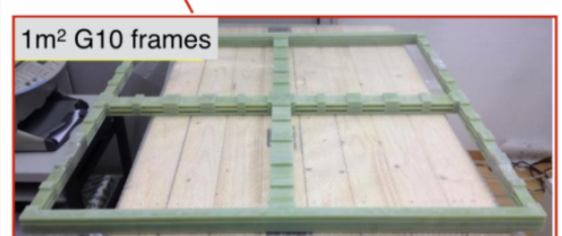


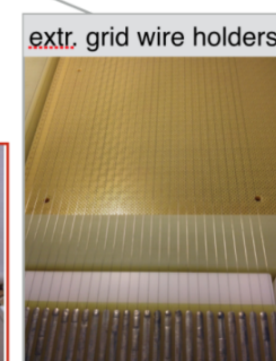
NP02: 4 CRPs







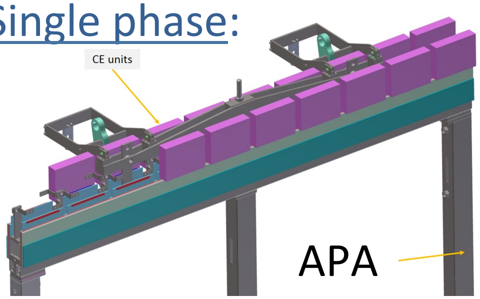




ProtoDUNE Cold Electronics

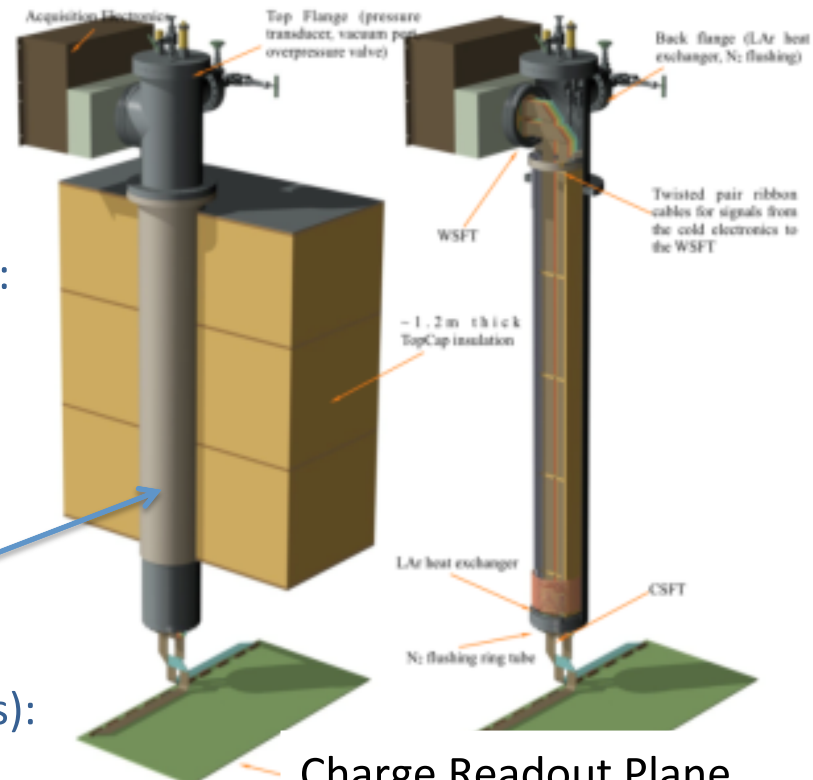
TPC electronics to be located close to wires resp. charge readout plane to minimize noise

Single phase:

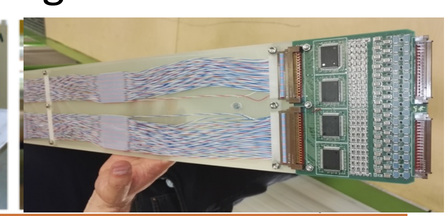


Inaccessible electronics boxes

Dual phase: accessible cold electronics



Charge Readout Plane



Cold electronics directly attached to APA (2560 wires):
1 APA → 20 FEMB (2560 ch/20 = 128 ch)

- Analog Mother board 128 wires IN
→ **Multiplexed** to 4 OUTputs
- Preamplifiers with shaping circuit

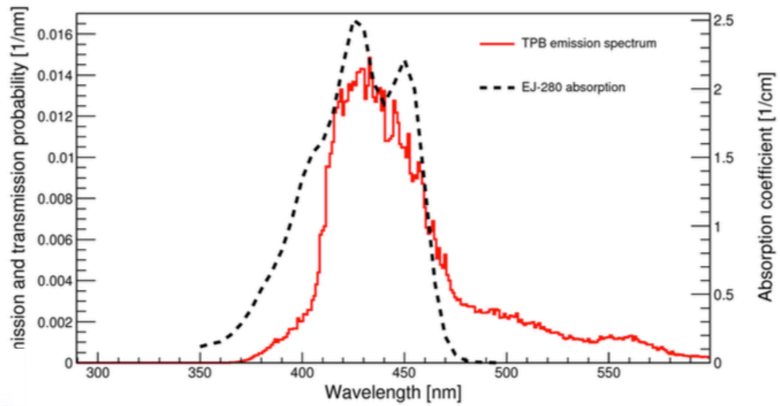
Dual phase:
Cold electronics in chimney (7680 channels):
16 channel ASIC, 1200 fC dynamic range

→ No zero suppression; no data compression

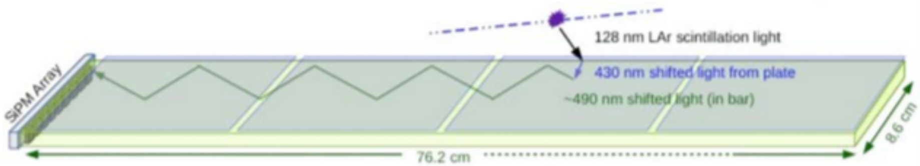
Photon Detection System (PDS)

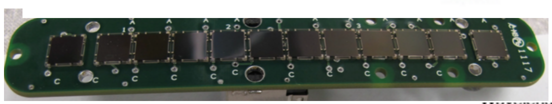
Purpose: provide t_0 for non-beam events, improved event reconstruction
Challenge: detection of LAr 128 nm (VUV) scintillation photons

Technique: use TPB to shift wavelength to ∼430 nm

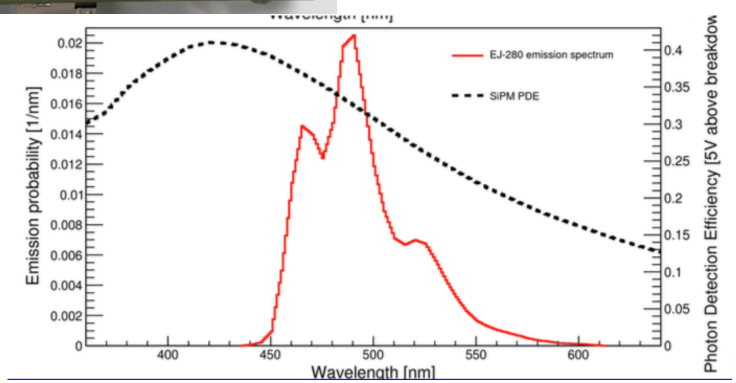


Single phase:
TPB coated acrylic bar coupled to wave shifter

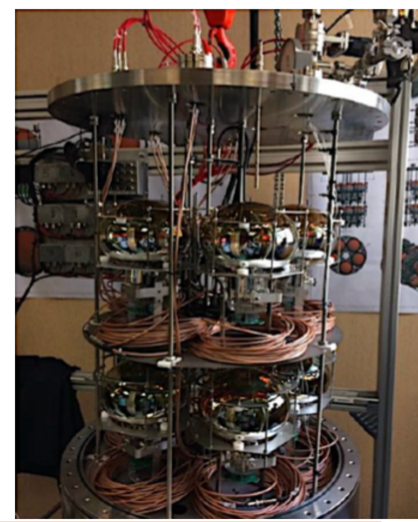




SiPM board



Dual phase:
8” Hamamatsu cryogenic PMTs
Coated with TPB



10 photon detection panels embedded in each APA

ProtoDUNE DAQ

ProtoDUNE Beam trigger rate: ~25 Hz, cosmics: ~10kHz

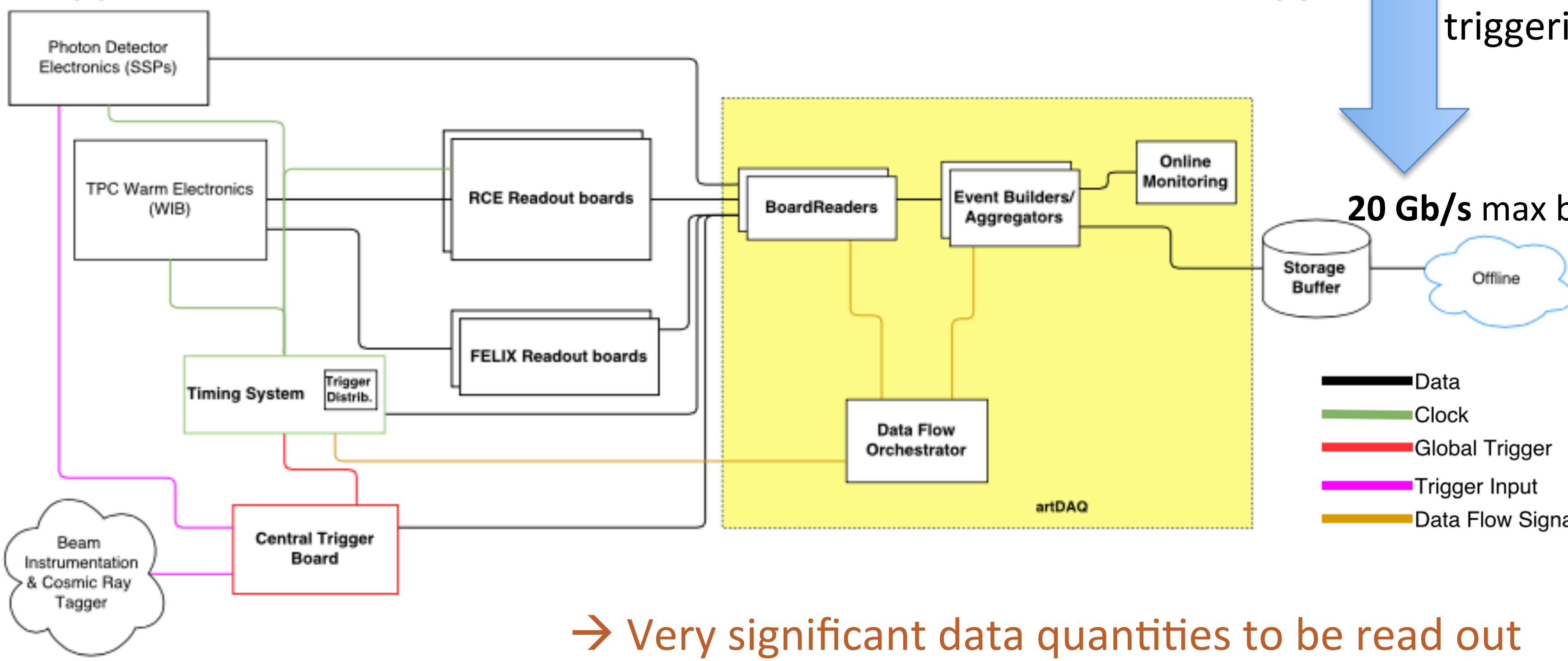
TPC: 6 APA (2560ch. Each) → 15,360 chan.; 2 MHz 12 bit ADC
→ raw pre-trigger rate: 480 Gb/s

PDS: 240 chan.; 150 MHz 14 bit ADC
→ 10 kHz self-triggered cosmic data rate: ~ 1.1 Gb/s

Trigger: beam instrumentation, photon detection system, muon tagger

Data reduction:
compression
triggering

20 Gb/s max bandwidth

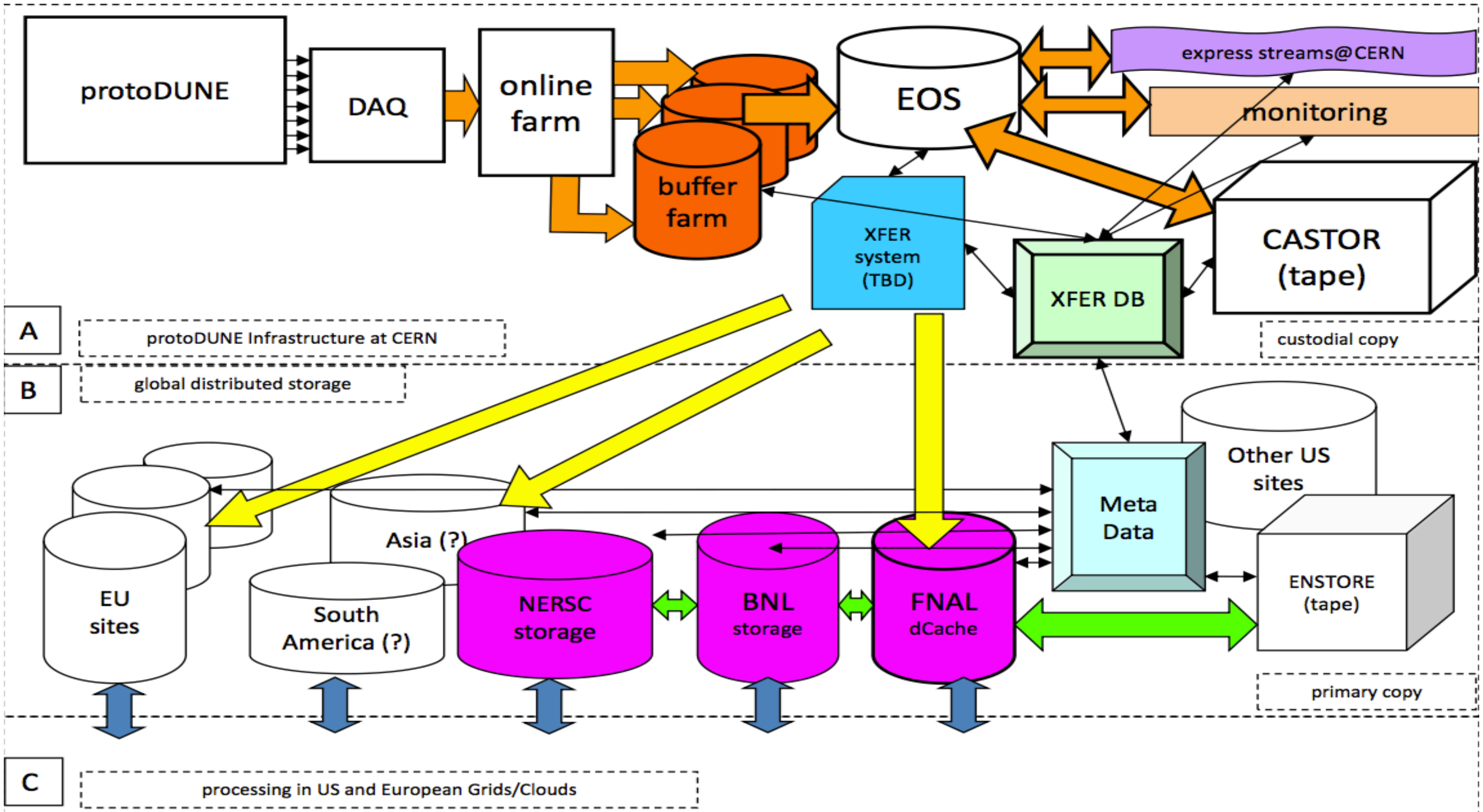


→ Very significant data quantities to be read out
DUNE: SNe bursts require ~10s continuous readout

Computing

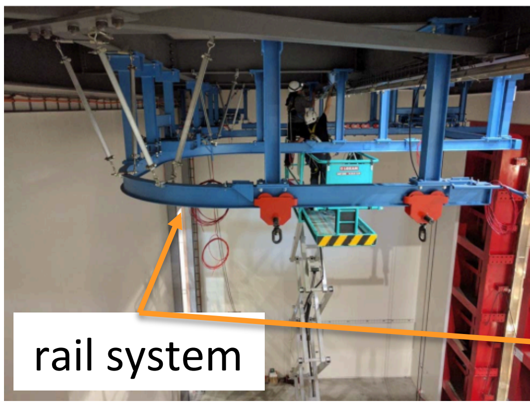
Common to both NP04 and NP02

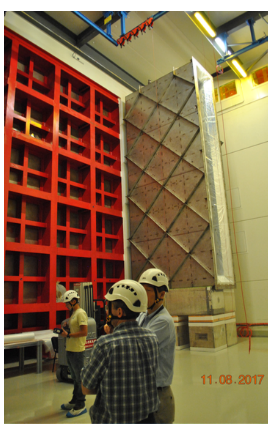
- Transfer raw data from online disk buffer to CERN EOS disk and onwards to tape (CERN: CASTOR; FNAL: ENSTORE) and other end-storage systems
- Collaboration of protoDUNE computing group with CERN-IT and FNAL-SCD

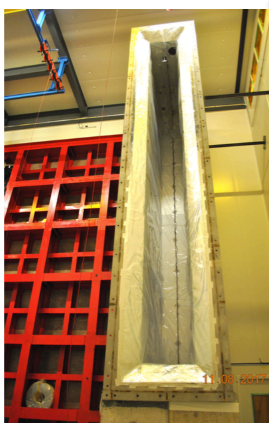


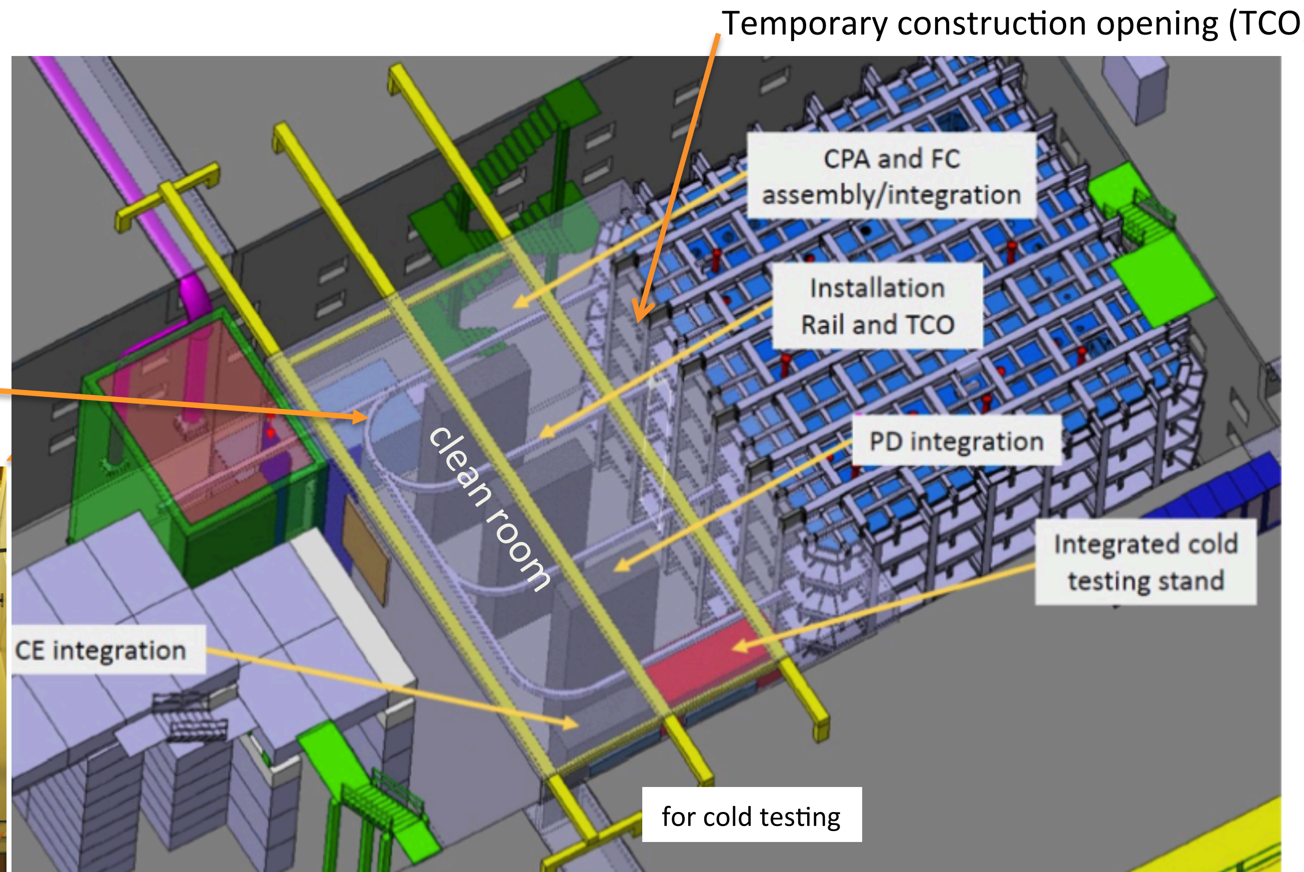
Integration, Testing and Installation

- Integration and tests of APA, CE and PD in clean room (dedicated cold box)
- The material for detector installation is brought to a clean room buffer and then via TCO into the cryostat
- Retest components once installed in final position

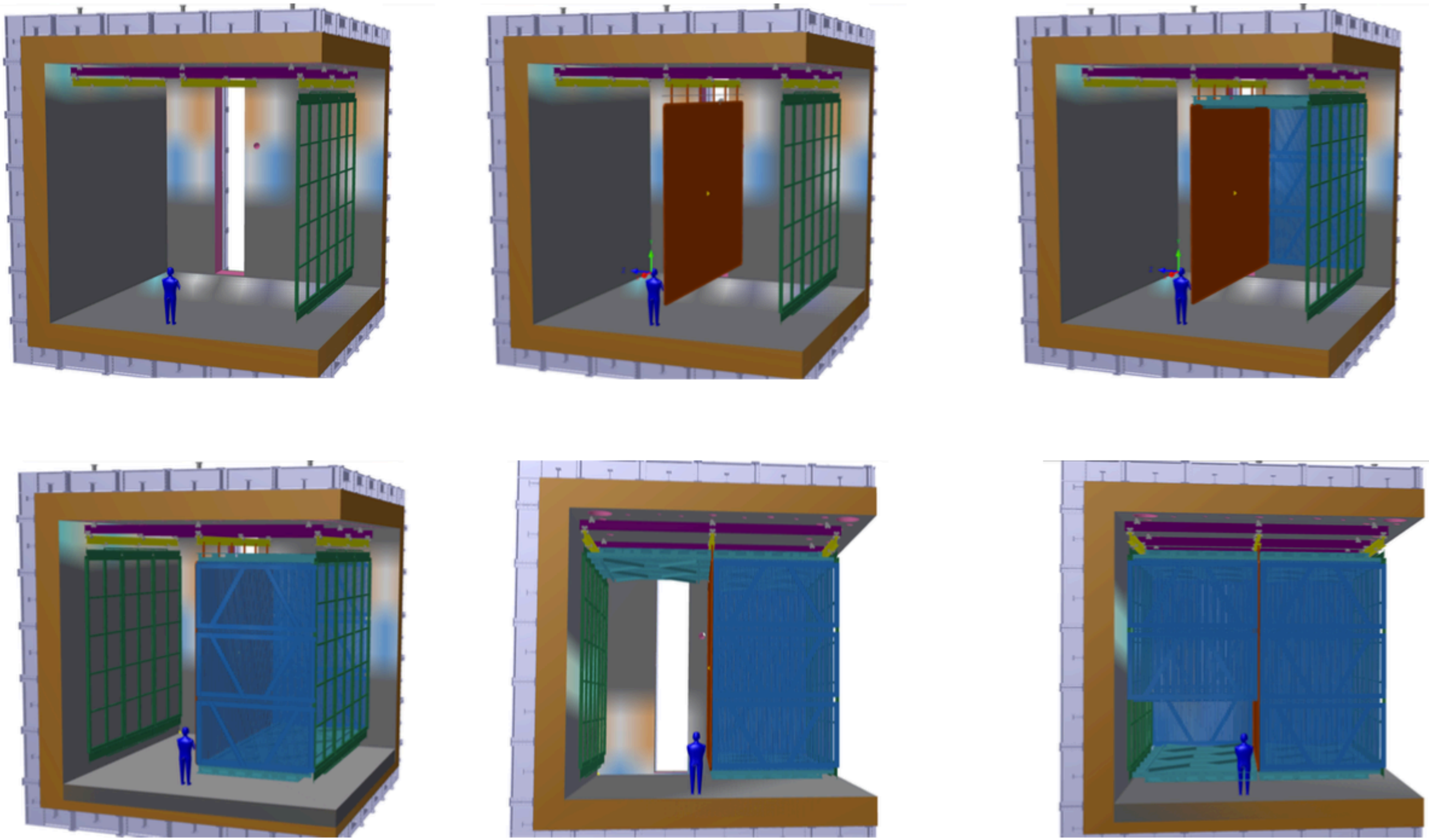








Installation in Cryostat

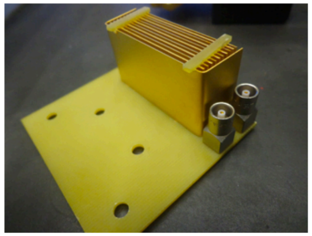


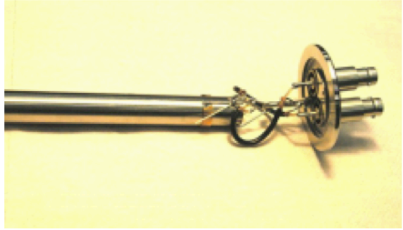
➔ Installation sequence same/similar as for DUNE 10kt modules

Slow Control System

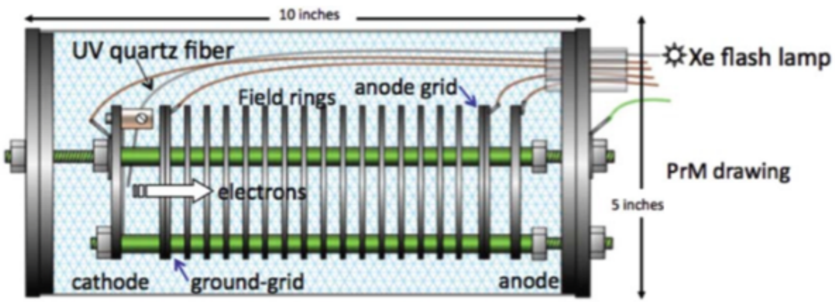
Common to both NP02 and NP04

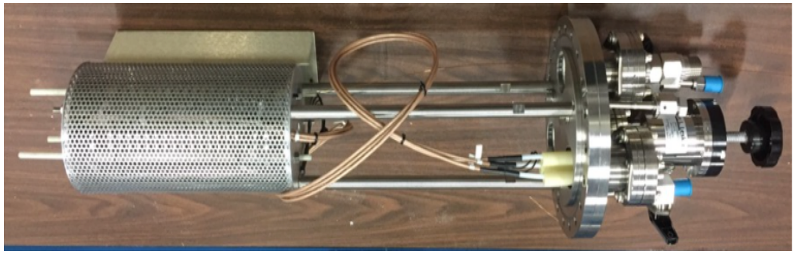
- Integrated control of level meters
- temperature and pressure sensors
- Gas analyzers
- Purity monitors



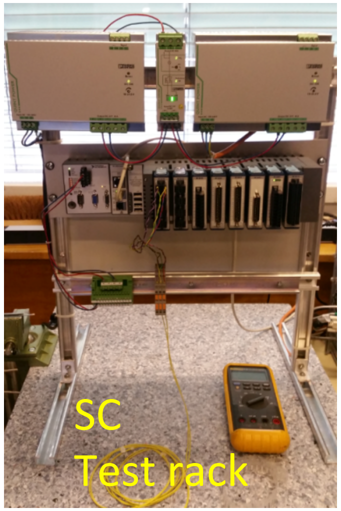


High accuracy (100 um)
and standard (1 mm) level meters





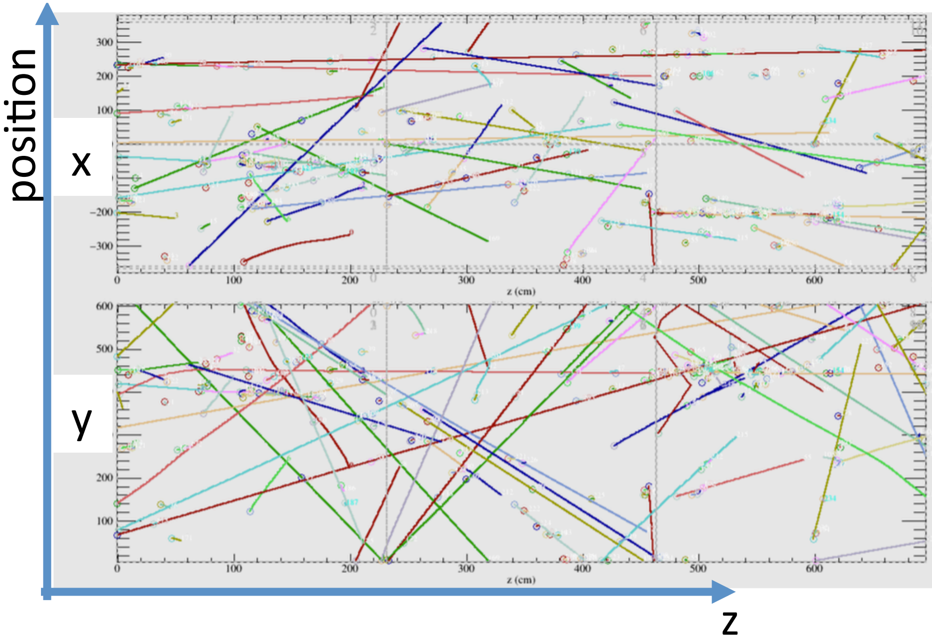
- Strain gauges
- Extensive network of sensors to completely characterize behavior of CRP
- Cryocamera



Cosmic Muon Tagging

Common to NP02 and NP04

Simulated cosmics in single phase TPC



Selected/tagged sub-sample of cosmics serve for calibration

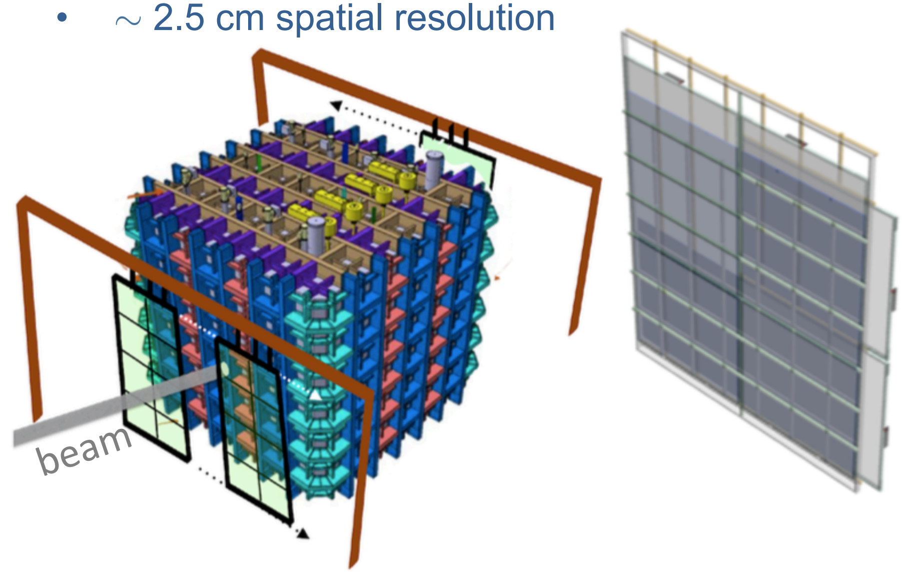
- LAr purity analysis
- Map field non-uniformities (track distortions)
- Study stopped muons + Michel electrons

→muon tagger (from Double CHOOZ):

- 3 (movable) panels, each composed of 4 units
- $\sim$ 2.5 cm spatial resolution

TPC (phase)	**Drift time [ms]**	**Readout wind. [ms]**	**Expec. μ/readout**
Dual	4	$\sim$ 8	80
single	2.25	$\sim$ 5	50

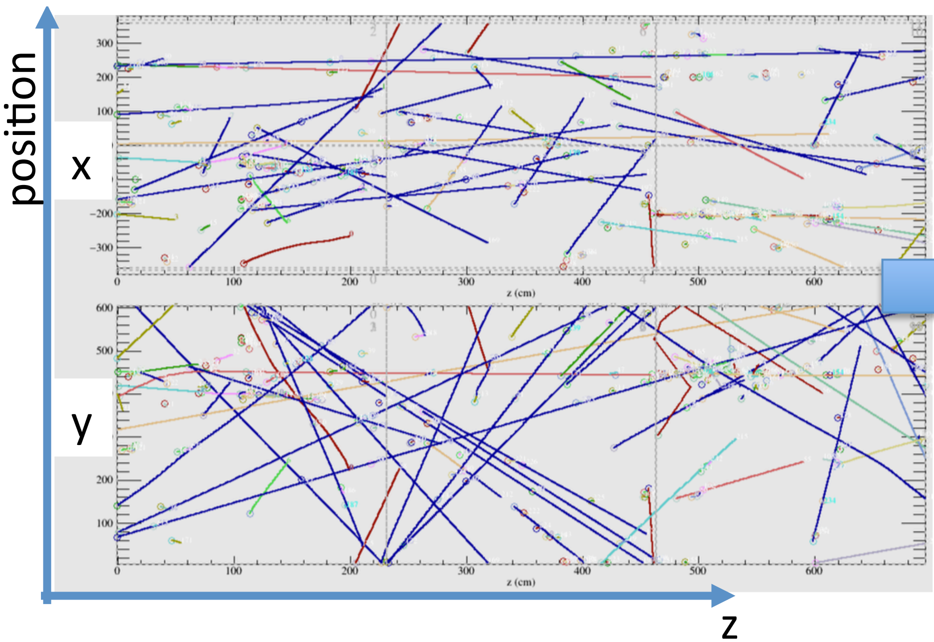
Increased readout window to identify track fragments in main event drift time



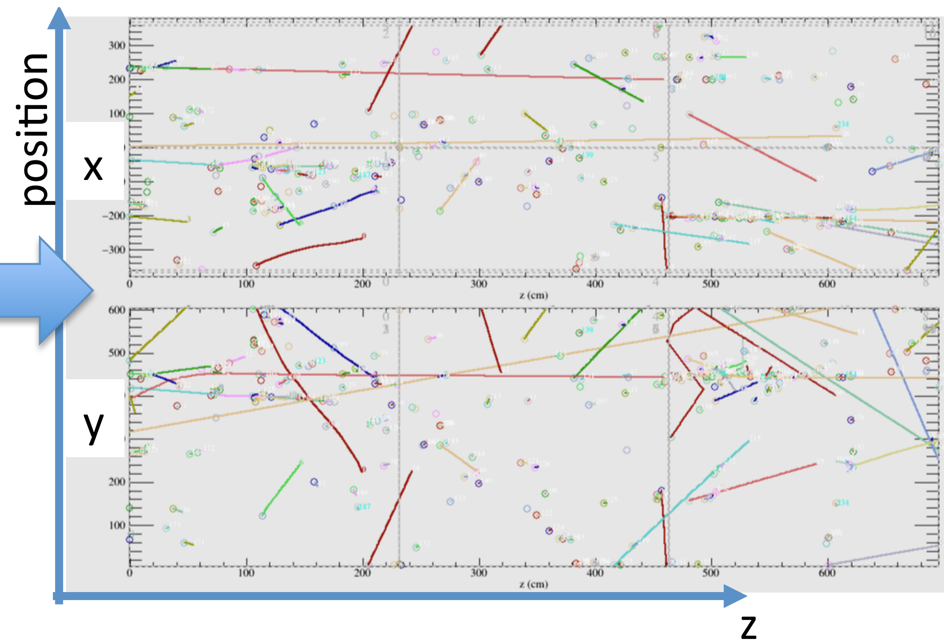
Muon Tagging

Common to NP02 and NP04

Tagged cosmics

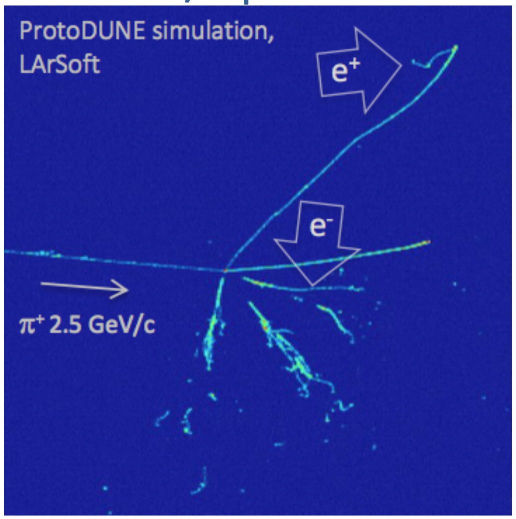


Cosmics removed

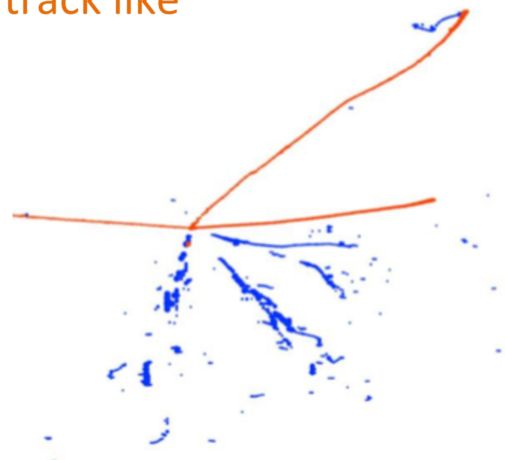


Event Reconstruction + Classification

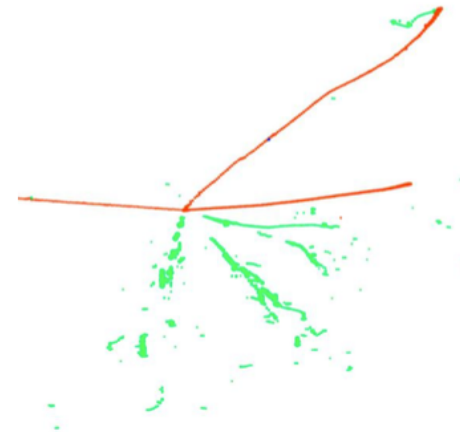
ProtoDUNE simulated
2.5 GeV/c pion event



<u>Convolutional Neural Network</u> (CNN)
Output: classification of individual hits as
EM like, track like



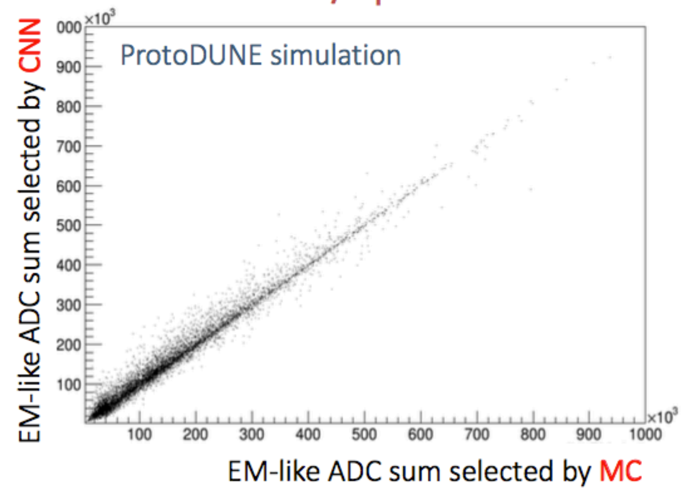
MC truth:
EM like, track like



High Precision image of particle interaction
→use machine learning technique developed in field of computer vision: <u>CNN</u>

Simulated sample of 4 GeV/c pions in ProtoDUNE:

4GeV/c pions

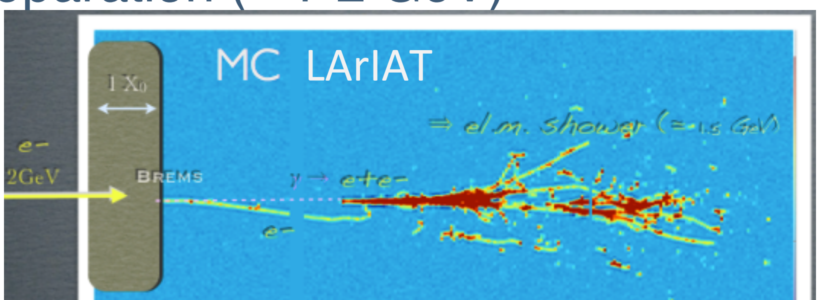


→ Have CNN also successfully applied to dual phase and LAriat data

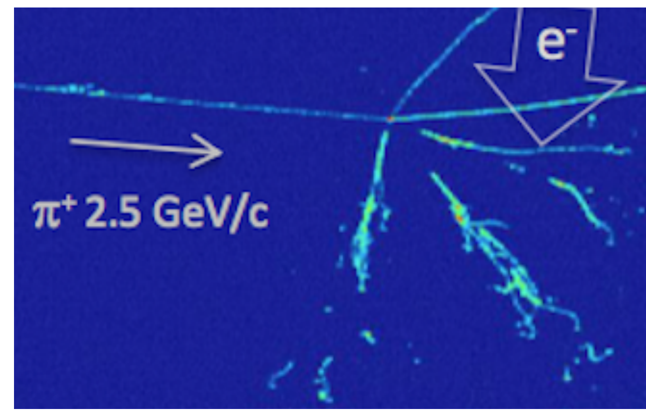
Anticipated Measurements

Pions/protons:

- Validate reconstruction tools, particle identification and simulations
  → Measure calibration constants (energy)
- Measure π^+/π^- differences and topological shower differences ($\sim$1 GeV)
- **Measure pion interaction cross sections**
- Measure π^0 for NC backgrounds and calibration
- Study e-γ separation ($\sim$1-2 GeV)



Study dE/dx along EM cascade



Study gamma conversion distance

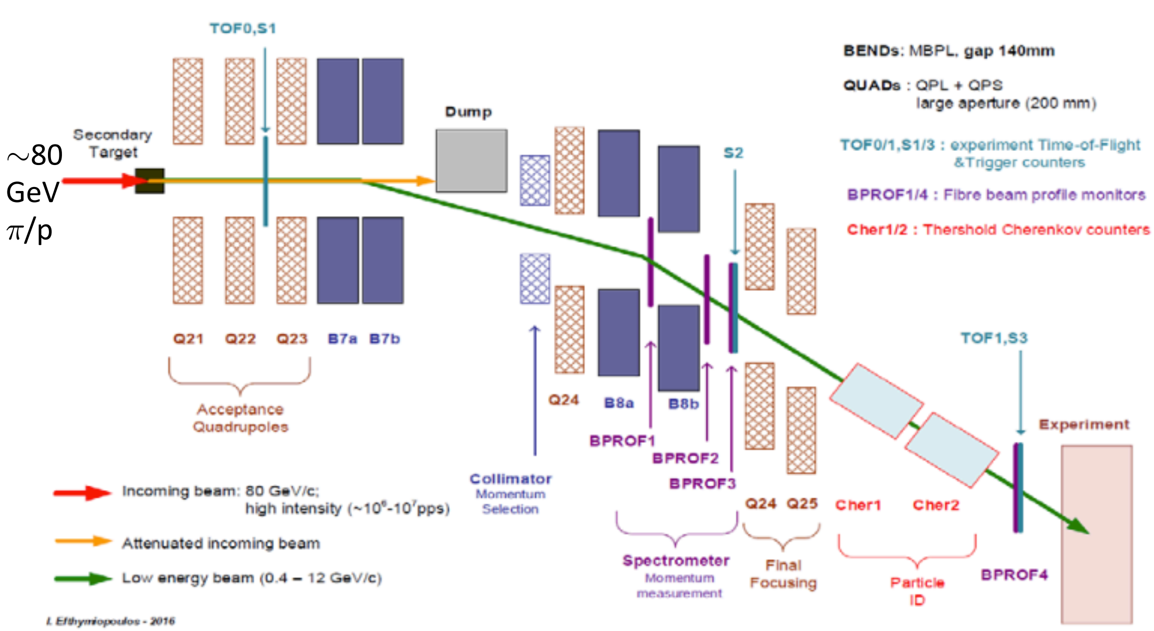
Electrons:

- Study e-γ separation (<2 GeV);
- Calibrate em showers (sub GeV – multi-GeV)

Muons:

- Study Michel electrons, calibrate Bethe-Bloch, study μ^- capture on Ar

Charged Particle Beams



Thanks to L. Gatignon (CERN), N. Charitonidis (CERN)

Schematic for H2 beamline layout

(H4 has one additional bending magnet)

beam instrumentation:

- Profile monitor (x,y)
- Particle tracking
- Momentum measurement

→ Fiber tracker

Particle ID:

→ Gas Cherenkov counters

→ TOF counters

Performed complete simulation of H2 and H4 beamline particle transport including

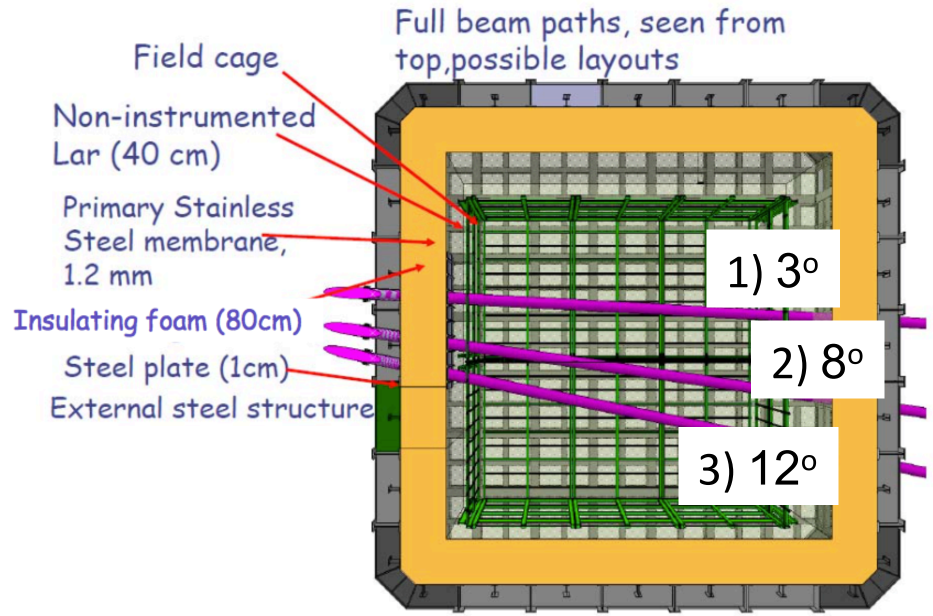
- Beamline monitors
- Detector beam window
- shielding

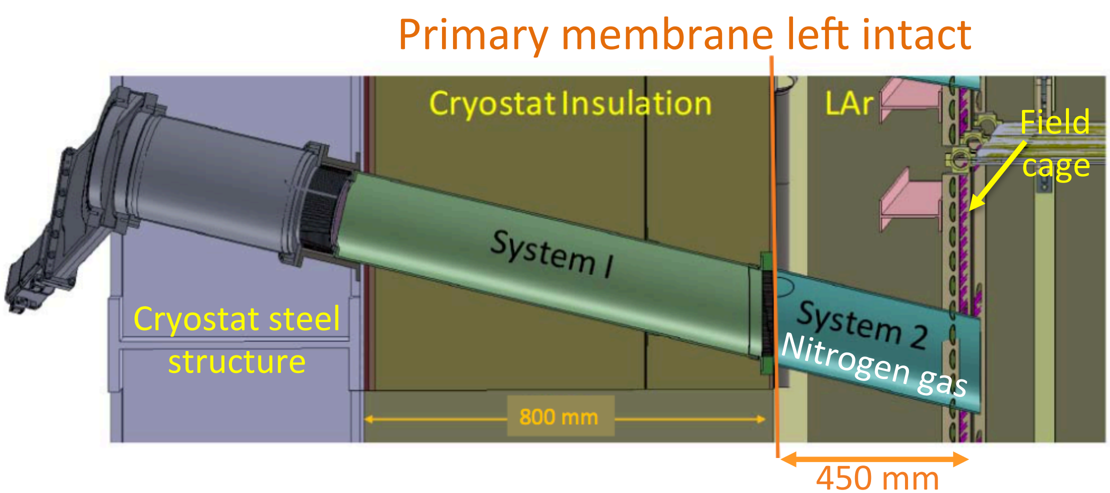
→ Mixed hadrons (π, p, K and e) rates below 1 GeV/c are low

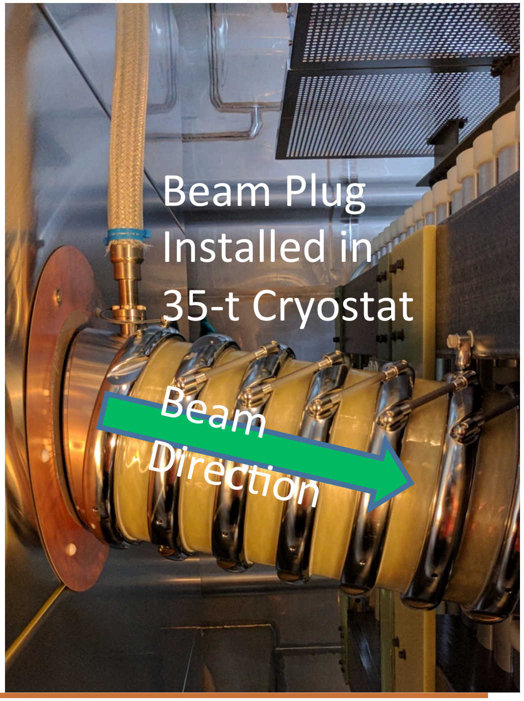
→ Relatively pure electron

Beam Window

From Fluka/G4 simulations:
→Lower E hadrons and electrons require full penetration to make it unscattered into active detector volume







→ Beam plug test in progress at FNAL

Beam composition + data sets

Positive beam

P (GeV/c)	# of Spills	# of e^+	# of K^+	# of μ^+	# of p	# of π^+	Total # of Events	Beam Time (days)
1	70K	84K	≈ 0	70K	689K	625K	1.5M	19.4 days
2	16K	19K	9K	36K	336K	572K	1.0M	4.4 days
3	13K	16K	26K	17K	181K	540K	780K	3.6 days
4	11K	13K	19K	16K	107K	510K	660K	3.1 days
5	11K	13K	29K	13K	96K	510K	660K	3.1 days
6	11K	13K	36K	12K	94K	510K	660K	3.1 days
7	11K	13K	42K	8K	87K	510K	660K	3.1 days
Total	143K	171K	161K	172K	1.6M	3.8M	5.9M	39.7 days

K decay causes depletion of lower energy K samples
→ long beamline: ~ 37m

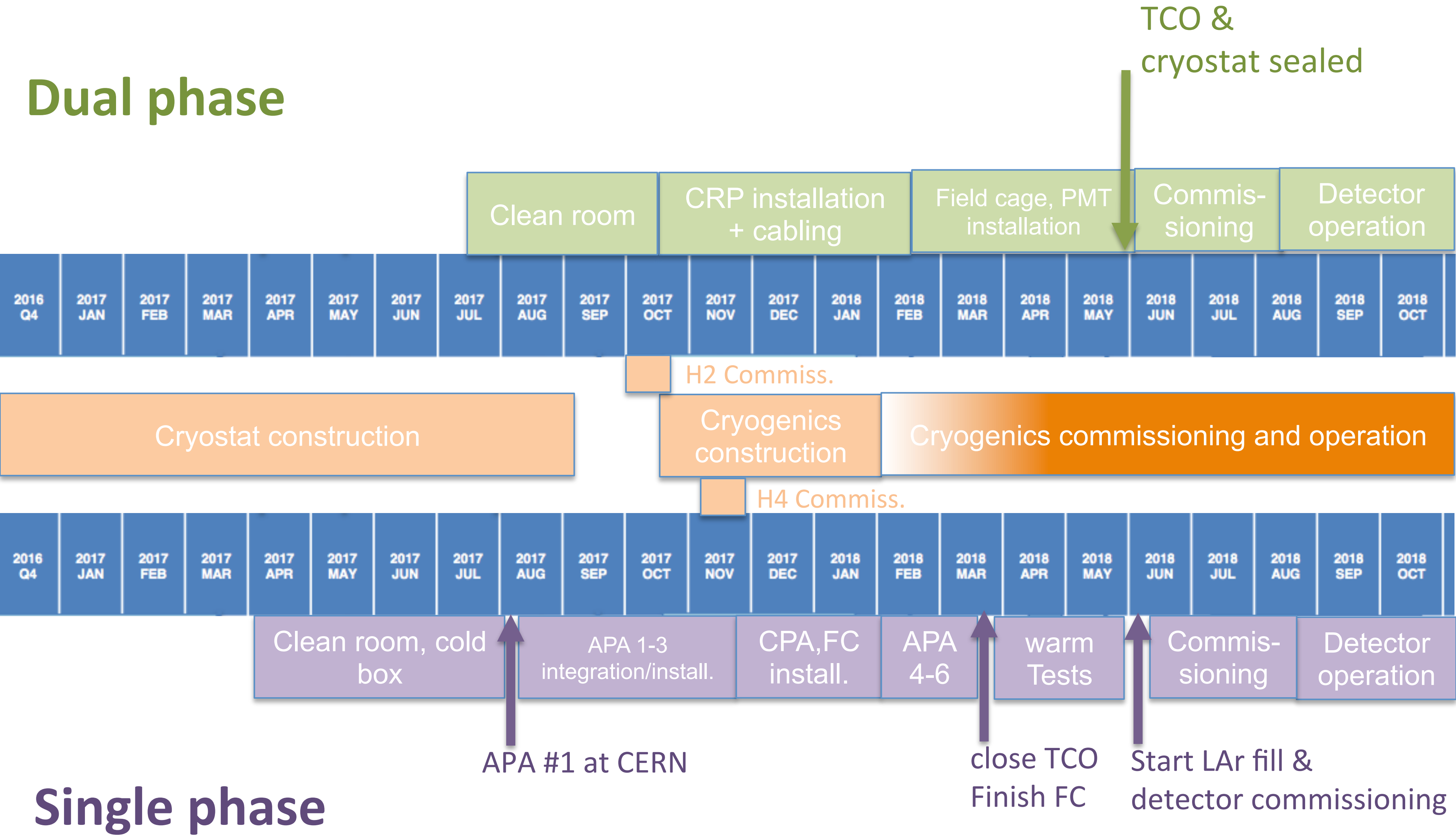
Momentum Bins (GeV/c)	# of Spills per Bin	# e^+ per Bin	Beam Time per Bin (days)
0.5, 06, 0.7, 0.8, 0.9, 1, 2, 3, 4, 5, 6, 7	5000	300K	1.4

Key assumptions:

- Trigger rate: 25 Hz
- Electron discrimination (rate reduced to 0.5 Hz) for hadron beam
- 50% data collection efficiency

→Total estimated beam measurement time is few months for positive and negative particles

Timeline



Approximate schedule summary from detailed project schedule

Other News

While ProtoDUNEs progress quickly at CERN, LBNF/DUNE is moving equally fast

Summary

- Provided an overview of the motivation, sub-components and measurements of ProtoDUNE LAr single and dual phase detectors

→ protoDUNE detectors are an important engineering milestone to
  - → perform full scale detector component tests in LAr
  - Validate performance of sub-systems (TPC,PDS, electronics) and their integration and installation
  - help to establish multiple production sites and QA procedures

→ measure charged particle response of full scale detector components
  - → validate MC simulations and particle interaction models
  - measure detector systematics
  - provide calibration data samples for future DUNE far detector

- Follow aggressive schedule - requires close and effective collaboration

→ Have strong international team on the ground